

SESSION III

FATE OF MARINE DEBRIS



CURRENTS OF THE TROPICAL AND SUBTROPICAL NORTH PACIFIC OCEAN

Gunter R. Seckel
P. O. Box 5322
Carmel, California 93921

ABSTRACT

Systematic observations of ocean properties began during the second half of the last century. These included the ship drift observations that became the foundation of our knowledge about ocean currents. Hydrographic station data collected aboard research vessels during the last 60 years greatly added to our understanding of the ocean circulation. During the last decade, the NORPAX satellite-tracked drifting buoy program provided information about the behavior of North Pacific surface currents that will be most helpful in learning how to predict the fate of marine debris. Using this information, the major tropical and subtropical ocean currents are described and the limitations in terms of predicting the fate of marine debris are discussed.

INTRODUCTION

Soon after he took to the sea, man must have learned about ocean currents and probably discovered that currents carry debris. Indians of the Puget Sound paddling their canoes certainly knew about tidal currents and the great navigators of the Pacific, the Polynesians, must have been aware of the equatorial currents and currents around their islands. All this knowledge was not broadly useful, however, without being recorded and published.

EARLY CURRENT CHARTS

As intercontinental ocean trade developed during the 17th century, the need for knowledge about the ocean and its currents became evident. During the next century, the Franklin-Folger Chart of the Gulf Stream (Fig. 1) was an early attempt to chart currents. It was not until the middle of the last century, however, that real progress was made in charting ocean currents. A very energetic, American hydrographer and pioneer oceanographer, Matthew Fontaine Maury, knew that ship captains kept detailed accounts in their logbooks of all environmental conditions they encountered including observations of winds, currents, and air and water temperatures. He realized that if this information were collected and summarized, valuable atlases could be produced and ocean currents could be charted. In a pilot study, he did just that and was able to

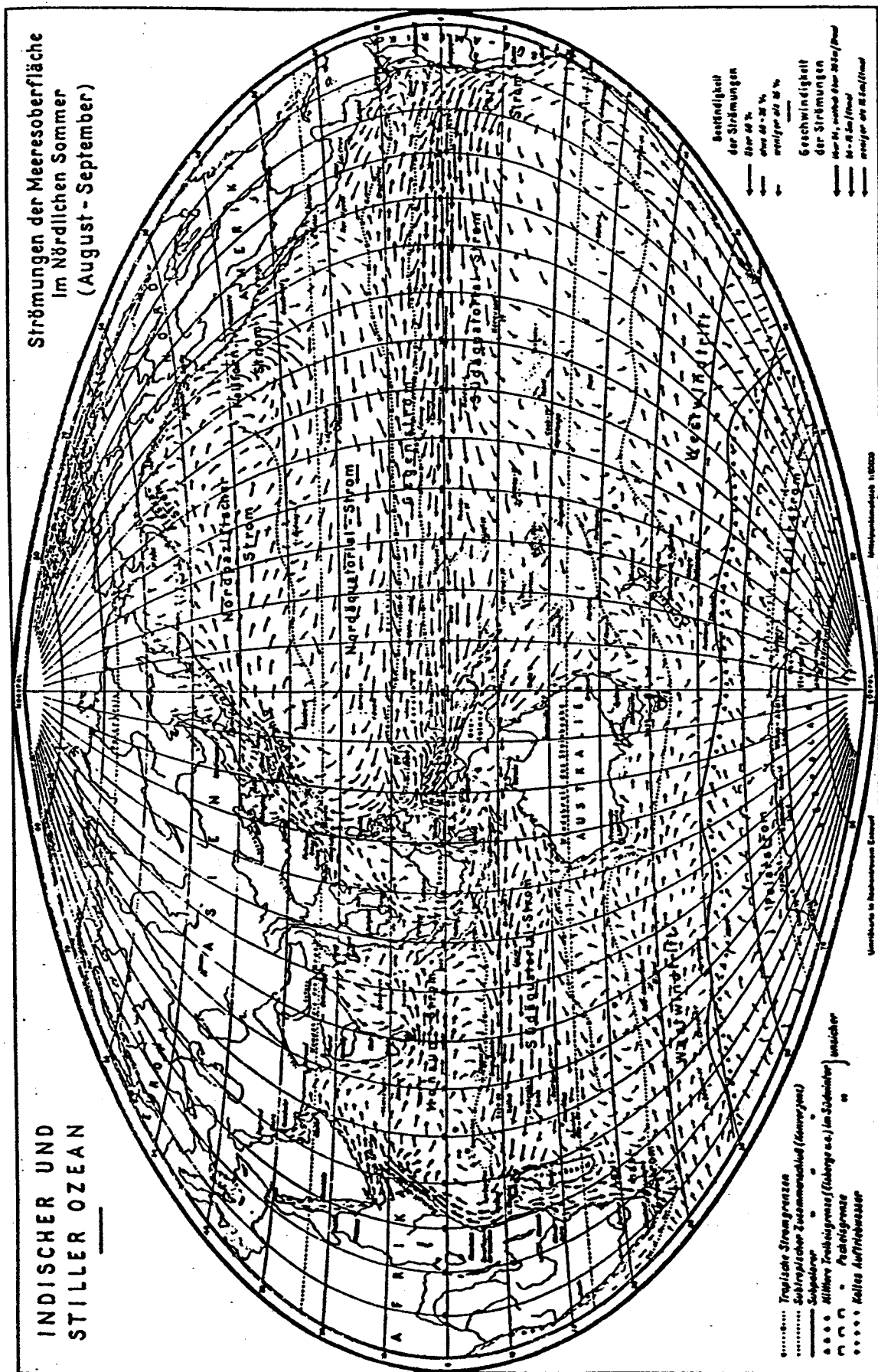


Figure 2a.--Currents of the Indian and Pacific Oceans (August-September) (Schott 1935).

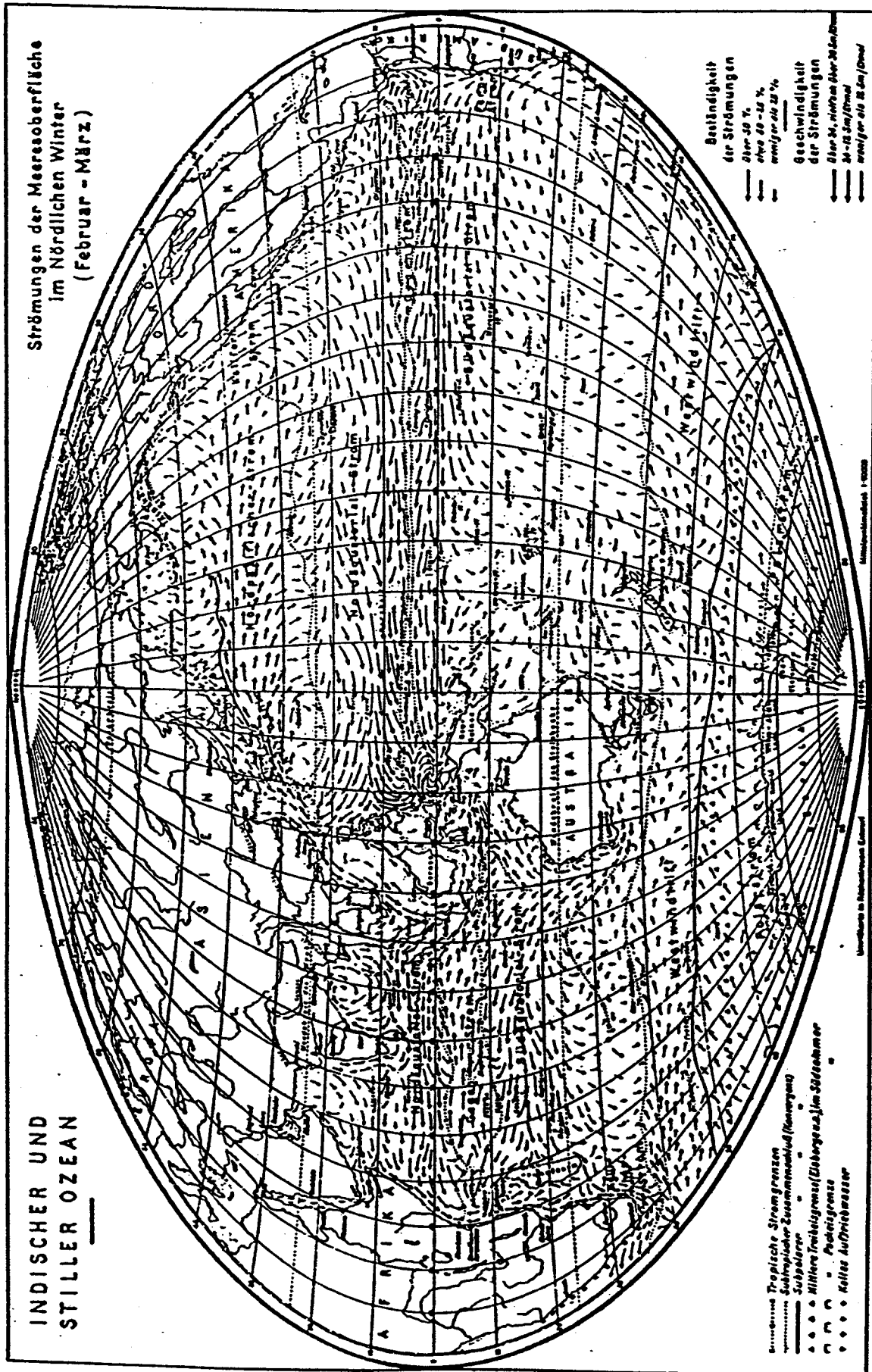


Figure 2b.--Currents of the Indian and Pacific Oceans (February-March) (Schott 1935).

currents are the following: In the western North Pacific, there is the strong, northeastward flowing Kuroshio and the eastward flowing North Pacific Current which is also called the West Wind Drift Current. On the eastern side of the ocean, the eastward flowing current splits into the northward flowing Alaska Current and the southward flowing California Current. To the south, between lat. 10° and 20° N is the westward flowing North Equatorial Current. These currents form the main segments of what is often called the subtropical gyre. South of the North Equatorial Current, between about lat. 5° and 10° N, there is the eastward flowing Equatorial Countercurrent. The westward flowing South Equatorial Current, which Schott shows to be very strong in the eastern half of the Pacific, lies south of lat. 5° N.

Interpretation of details in these charts must be made with caution. Although many thousands of observations went into their production, ship-drift determinations are subject to relatively large errors. Nevertheless, interseason differences can be noted, such as, changes in the intensity, width, and shifts in location of currents. For example, the Equatorial Countercurrent which Schott shows to be wide and well developed during the summer in the eastern half of the Pacific is narrow or almost absent during the winter. I will return to a discussion of this current later.

Although current charts such as those produced by Schott have been updated and refined, they show no major changes of the basic flow pattern he described. Useful charts for mariners are the Pilot Charts which are produced for each month by the Defense Mapping Agency.¹ These charts primarily give meteorological information, but they also show the currents for each month (again based on ship-drift data). An example is shown in Figure 3.

GEOSTROPHIC CURRENTS

While merchant ships routinely were collecting meteorological and oceanographic data, oceanography as a separate discipline developed with research expeditions that explored all the oceans. Important on these expeditions were vertical soundings for water samples so that temperature and salinity versus depth profiles could be determined at many locations of the oceans. With this information, after calculating first the density and then the potential height of the sea surface above a given reference level, it was possible to chart the dynamic or geopotential topography of the sea surface. This information is used to determine the ocean circulation indirectly.

Reid (1961) used the data from many research expeditions to produce a chart of the geopotential topography for the Pacific (Fig. 4). Interpretation of the chart in terms of the geostrophic currents is similar to the interpretation of atmospheric pressure charts in terms of geostrophic winds. Flow is along the contours; when the contours are close together, the flow is fast and when they are far apart, it is slow. The

¹[U.S.] Defense Mapping Agency, Department of Defense, Pilot chart of the North Pacific Ocean. (Monthly.) Washington, D.C.

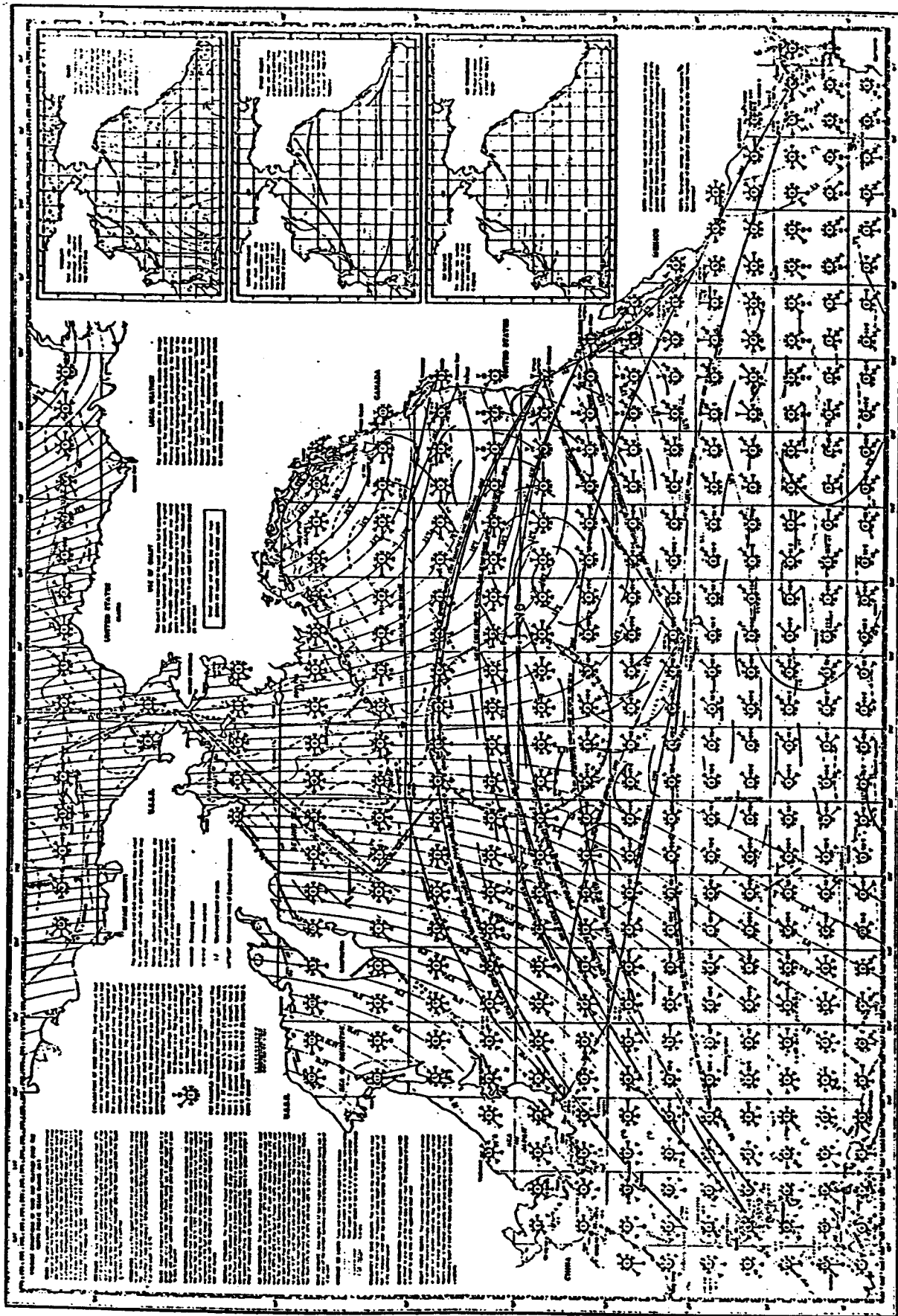


Figure 3.--Pilot chart of the North Pacific, July 1984.

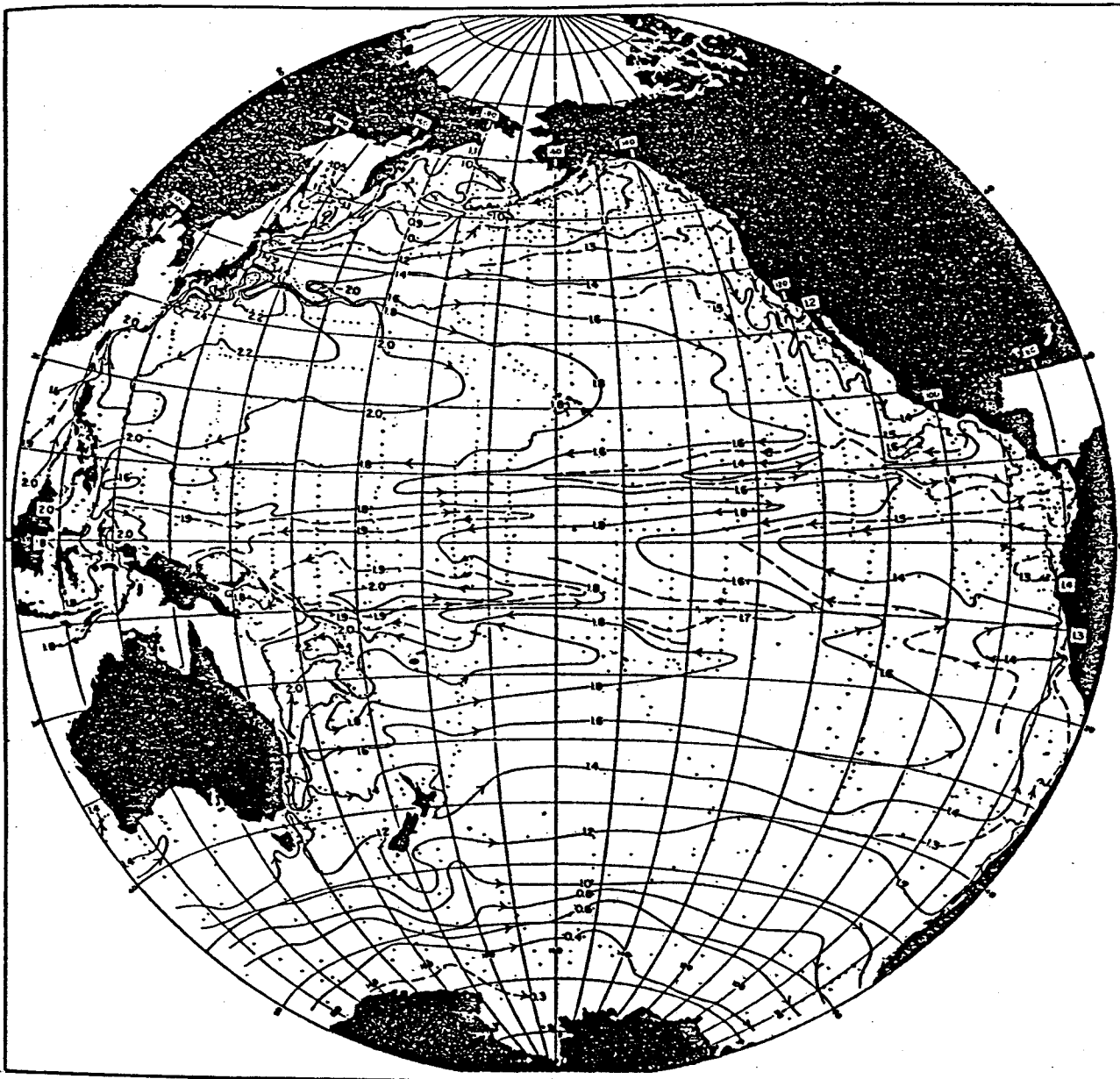


Figure 4.--The anomaly of geopotential distance between the 0- and 1,000-decibar surfaces in the Pacific Ocean, in dynamic meters (Reid 1961).

geostrophic interpretation cannot be used on the Equator and becomes uncertain within 1° to 2° of latitude of the Equator.

The geostrophic current is an idealized current in which a steady state (no acceleration) and no friction are assumed. Also, the geopotential topography does not reflect the wind-induced surface drift. Nevertheless, the subtropical gyre with the major currents as described before can be recognized. Note the closely spaced contours near Japan indicating that the Kuroshio is a fast current. Also note the wide spacing between contours in the central North Pacific indicating a slow net flow. Again, the North

Equatorial Current, the Equatorial Countercurrent, and the South Equatorial Current are clearly evident. Through the use of large data banks in modern computers, new geopotential height charts have been produced. However, they do not differ materially from Reid's chart shown here.

THE EQUATORIAL UNDERCURRENT

There is one important current that has escaped detection by both the ship-drift and the dynamic topography method of mapping ocean currents. This current is the Equatorial Undercurrent which is also called the Cromwell Current because it was first recognized by Townsend Cromwell in 1953. Cromwell was an oceanographer at the Pacific Oceanic Fishery Investigations (POFI) Laboratory (now called the Honolulu Laboratory, Southwest Fisheries Center). While participating on an exploratory fishing cruise, he noted that a longline set out on the Equator was drifting in the "wrong" direction, namely to the east rather than to the west, the direction of the South Equatorial Current. He suspected and subsequently confirmed the existence of the subsurface current (Cromwell et al. 1954).

Since its discovery, the Equatorial Undercurrent has become the subject of many investigations and has been described through direct current meter measurements. The results of early measurements at long. 140°W are shown in Figure 5 (Knauss 1960). The current profiles show the core of the current to be at a depth of about 100 m with speeds of more than 2 knots (>100 cm/s). Eastward flow extends from about 30 m to more than 200 m and from about lat. 2°S to 2°N. The current extends all the way from the Galapagos Islands to the western Pacific, long. 150° to 160°E. The boundaries of the current as well as its maximum speed may vary with time and it has been observed to come to the surface during El Niño years.

Excepting the occasions when it comes to the surface, the Equatorial Undercurrent may not be important in terms of carrying drifting debris. However, subsurface fishing gear may become hopelessly tangled when set out on the Equator because of the large shear produced by the strong westward flowing surface current and the equally strong eastward flowing subsurface current. Thus, the tangled gear, if not recovered, will contribute to the drifting debris in the ocean.

OBSERVATIONS OF CURRENTS USING MODERN TECHNOLOGY

Ocean current charts based on ship-drift determinations or geopotential height calculations provide only gross pictures of ocean currents because they are based on averages of many observations made over a period of many years. These charts will give us a general idea where drifting debris may eventually end up but they cannot provide the information that is important for the prediction of debris paths, namely information about eddies, periodic fluctuations, or interannual variations of the currents.

During the last decade, a direct method of measuring ocean currents has become feasible. This method simply involves tracking the position of a drifting buoy with an attached drogue by satellite. These buoys are sometimes called Lagrangian drifters because it is possible to plot the path of a parcel of ocean water, assuming that the buoy stays in the same

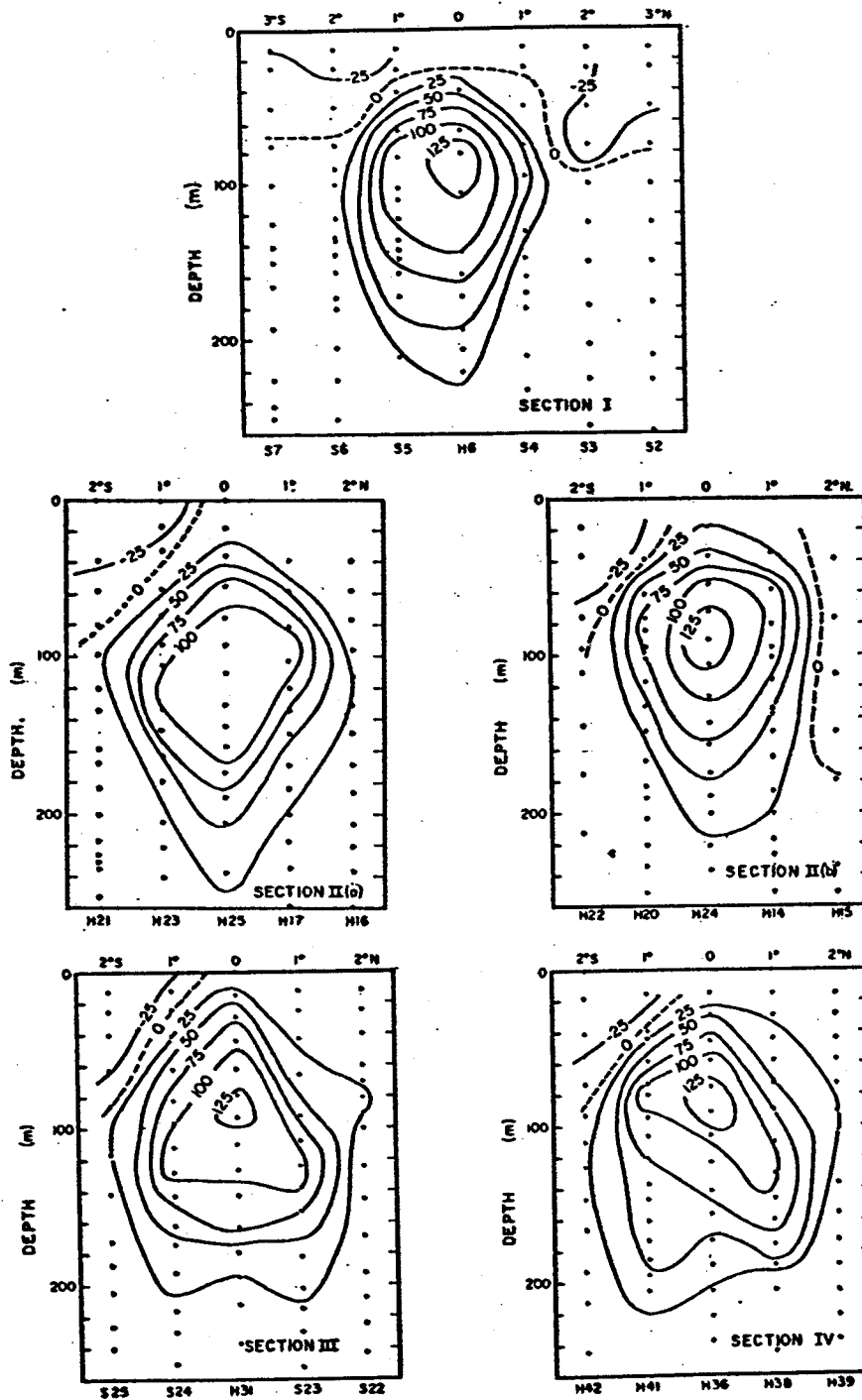


Figure 5.--Velocity cross section at long. 140°W. Dots are observed points, velocity is in cm/s; plus is eastward- and minus is westward-flowing current. Section I, 6-9 April, section II, 12-18 April (two sets of data), section III, 20-22 April, section IV, 23-27 April (Knauss 1960).

parcel of water. The drifting buoy method is really quite old but was not feasible on a large scale because it required a ship to stand by to record the changing position of the buoy.

RESULTS OF THE NORPAX DRIFT BUOY PROGRAM

During the last decade, about 130 satellite-tracked drifting buoys were deployed in the North Pacific as a part of the North Pacific Experiment (NORPAX). The buoys consisted of 3 m long fiber glass cylinders, 39 cm in diameter, ballasted to float vertically 1 m above the sea surface. The buoys were drogued at a depth of 30 m with a 9-m diameter personnel parachute. McNally et al. (1983) summarized the results of the program in terms of the near surface circulation of the North Pacific by describing the paths of 16 drifters (Fig. 6). We see that, in general, the paths conform to the current pattern previously described. More detailed analysis by the authors indicates that in the northern limb of the gyre, east of long. 170°W, the near surface flow has a large annual signal that correlates with the annual signal in the westerlies. In the eastern and southern limbs of the gyre, the drift trajectories tend to cross the

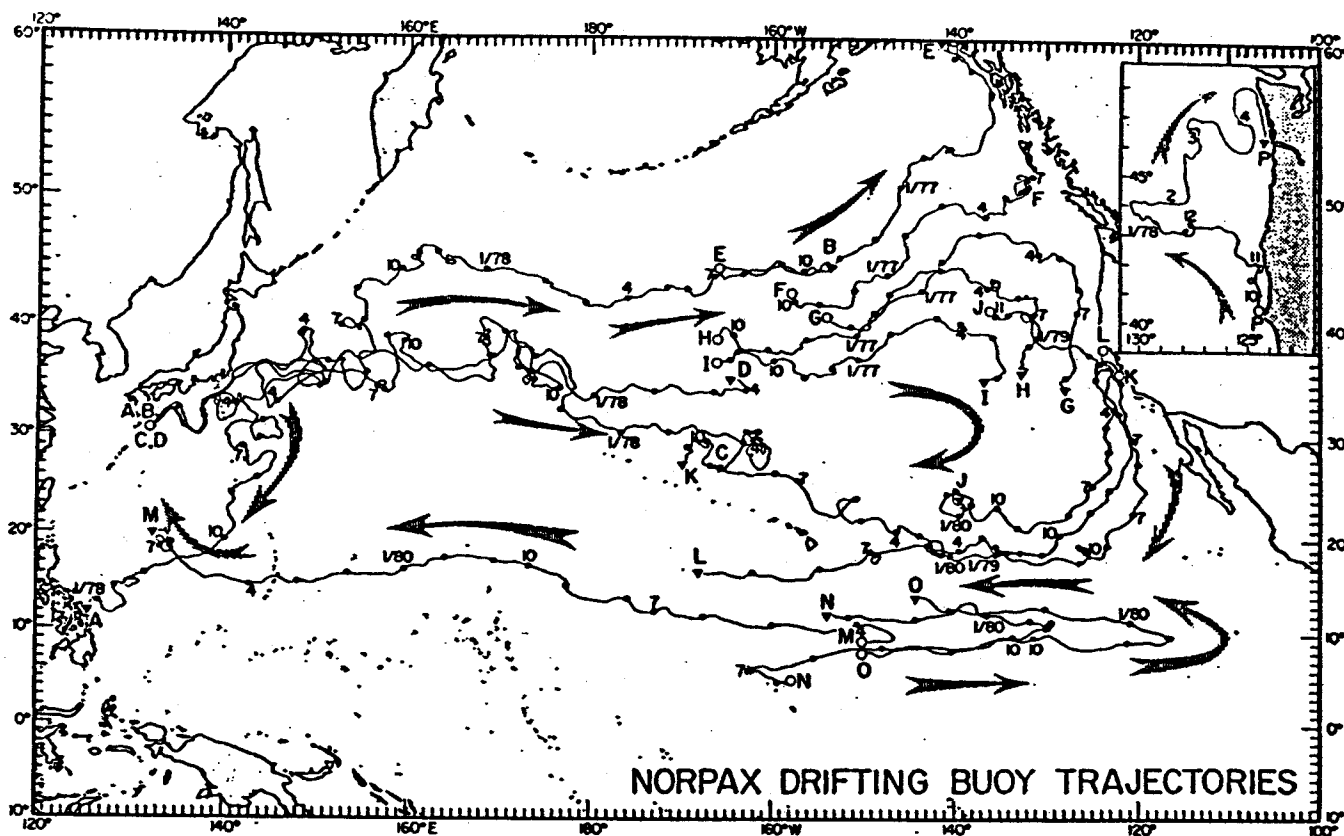


Figure 6.--Trajectories of 16 satellite-tracked drifting buoys deployed from 1976 through 1980 during various experiments. Open circles indicate the deployment locations, solid circles indicate the first day of each month, and triangles indicate the last reported locations. The large stippled arrows show the directions of the trajectories (McNally et al. 1983).

contours of the dynamic topography to the right. Both of these results indicate the importance of the wind-driven surface flow in determining the paths of drifting debris. McNally et al. found that the drifter speeds in the western limb of the gyre are the highest found around the gyre, which agrees with the geostrophic speeds evident in Figure 4. In the Kuroshio extension, just east of Japan, the drifter paths reflect the complicated nature of the circulation which is also evident in the dynamic topography shown in Figure 4.

The results of the drifter program provided some interesting statistics. The drifter trajectories traversed 20,845 km in 1,653 days (4.5 years) with an overall average speed of 15 cm/s (about a third of a knot). Average speeds around the gyre ranged from 10 to 17 cm/s. The transit time across the Pacific going east in midlatitudes and west in the equatorial regions was approximately 700 days (about 2 years) in each. Speeds of selected drifters in the major currents were as follows: Kuroshio - 61 cm/s, Kuroshio extension - 15 cm/s, North Pacific - 10 cm/s, California - 15 cm/s, North Equatorial - 17 cm/s.

McNally (1981) analyzed the wind-buoy trajectory relationships of those satellite-tracked drifters of the NORPAX program that were set out in the central, midlatitude North Pacific (Fig. 7). He found that when the monthly average wind direction in an area 5° of latitude by 5° of longitude was compared with the monthly average buoy drift direction during fall, winter, and spring, the buoys drifted to the right of the wind direction with a difference angle of 28° . (Drift to the right of the surface wind was first observed by Nansen during the Norwegian North Polar Expedition at the end of the last century (Nansen 1902). This observation became the basis for fundamental theories in oceanography.) Using 5-day running averages of four times daily determinations of the wind and drift vectors, McNally plotted histograms which show that at wind speeds of below about 2.5 m/s, this relationship did not hold. The overall monthly windspeed increased from a minimum of 2 m/s in August 1976 to 10 m/s in January and February 1977. This explains why the relationship between wind and direction of drift was not observed during the summer. The drifter speeds were approximately 1.5% of the wind speeds. The drift pattern during the summer of 1976 (Fig. 8) is one of slow, eastward eddying flow.

At some time during their life, buoys lost their drogues. This gave McNally an opportunity to compare the behavior of undrogued drifters with drogued drifters. He found that the difference in speed and direction was small and concluded that there was a lack of vertical shear in the horizontal currents of the upper 30 m during periods of strong and persistent atmospheric forcing. Additionally, one can conclude that the direct effect of the wind on the drift of the buoys also was small.

THE NORPAX DRIFTER EXPERIMENTS AND VARIABILITY OF CURRENTS

A most interesting result of McNally's (1981) study, in terms of predicting the drift of debris, is reproduced in Figure 9. The buoy displacements from the beginning to the end of the month are plotted on the mean sea level atmospheric pressure chart for December 1976, January, February, and March 1977. The buoy drift was parallel to the isobars.

This relationship is explained by the fact that observed winds tend to be directed 20° to 30° to the left of the geostrophic winds which are parallel to the isobars, and the buoy drift is directed 20° to 30° to the right of the wind direction. The result shows that as the sea level pressure pattern and, therefore, the wind pattern changed from month to month during fall and winter, so did the surface current.

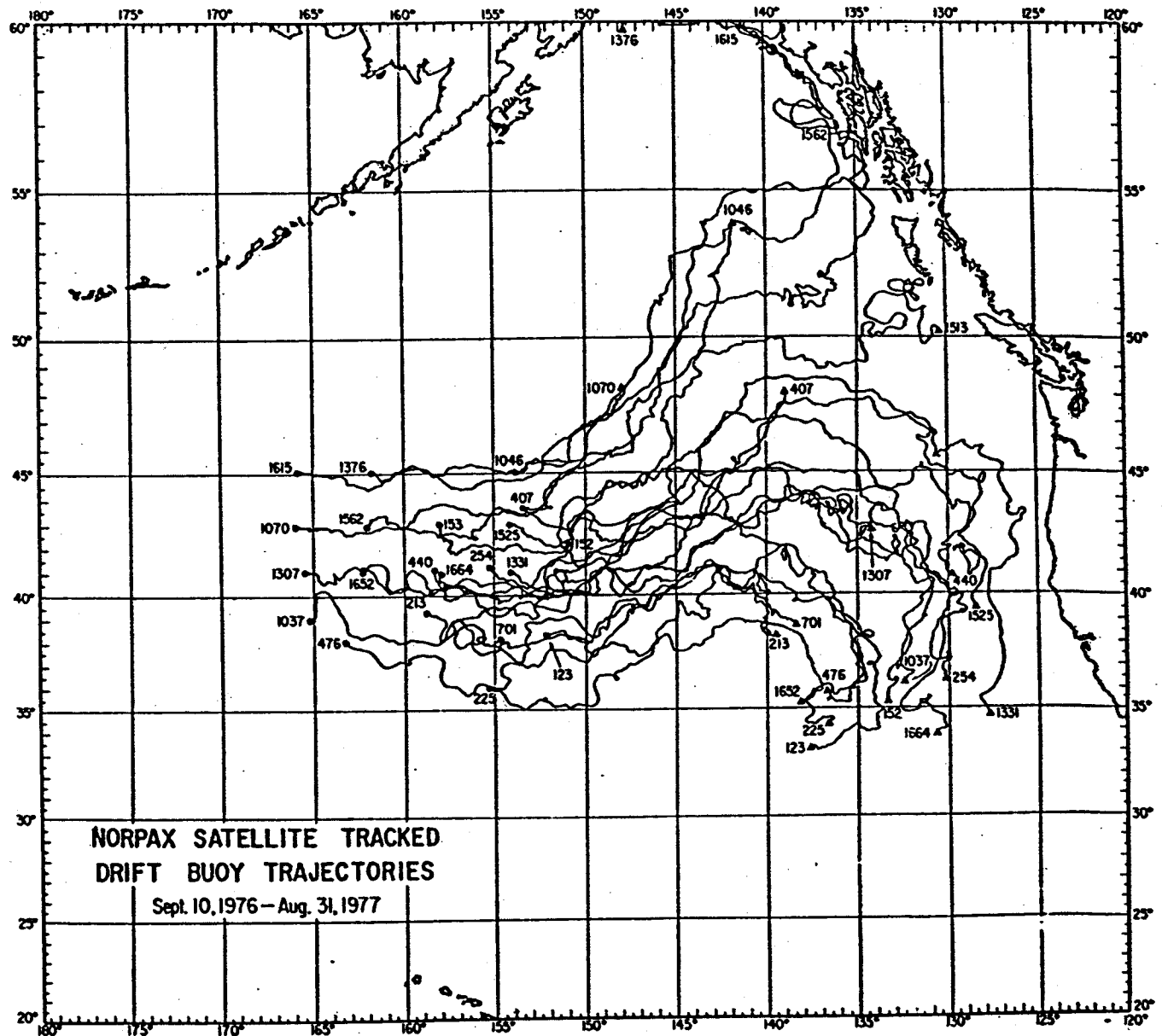


Figure 7.--Trajectories of drifters for the period September 1976 to August 1977. Solid dots indicate initial positions; solid triangles indicate last position (McNally 1981).

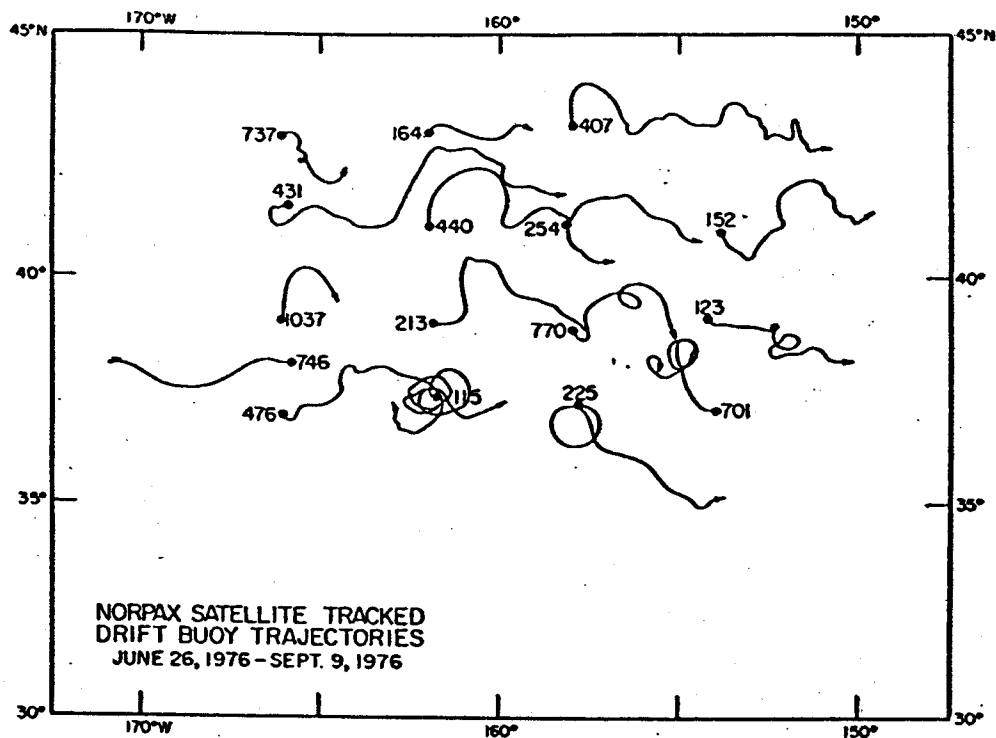


Figure 8.--Trajectories of drifters for the period June 1976 through September 1976. Solid dots indicate initial position; solid triangles indicate last position (McNally 1981).

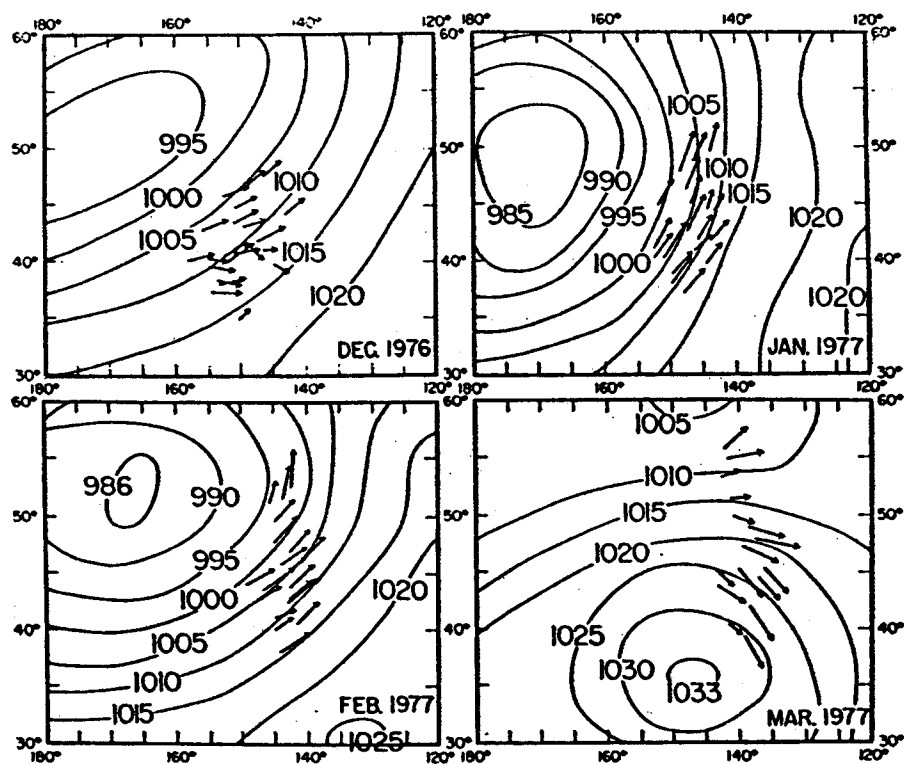


Figure 9.--Drifter positions superimposed on monthly mean sea level pressure charts. The arrows indicate monthly displacements of individual drifters (McNally 1981).

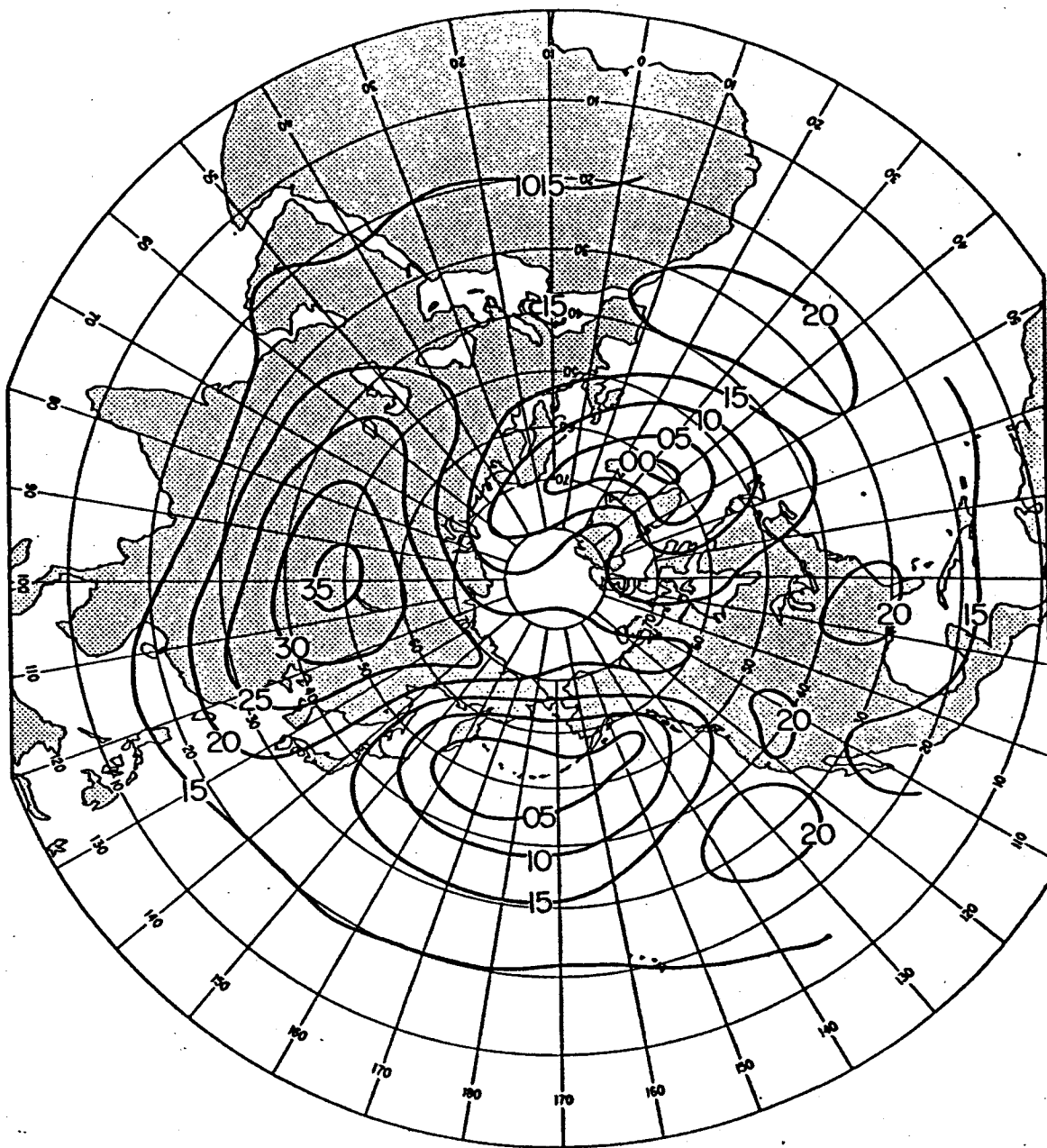
If the drift monthly mean pressure relationship shown in Figure 9 holds during other years and is not caused by the atmospheric circulation peculiar to the fall and winter of 1976-77, then, on the basis of sea level pressure charts, one can infer large interannual variations in the surface currents of the midlatitude Pacific. Mean winter (December, January, and February) sea level pressure charts (Namias 1975) are used to illustrate interyear differences. Figure 10a, the 1947-72 mean winter pressure distribution, is included for reference showing the Aleutian Low as a single low pressure system. During the winter of 1955-56 (Fig. 10b), this low is split into a western and an eastern low pressure cell, separated by a pressure ridge between long. 160°W and 180° . Using the convention of Figure 9, one would infer an entirely different surface circulation than one would from the pressure distribution such as in Figure 10a. In another example, during the winter of 1956-57 (Fig. 10c), high pressure in the eastern North Pacific has shifted the Aleutian low to the west. One can postulate that in the pressure ridge region, wind speeds would be low and that the drifters would behave more like they did in summer of 1976, without a relationship to the wind.

The NORPAX drifter program also confirmed pronounced annual variations in the Equatorial Countercurrent that already were apparent in Schott's (1935) charts. During the Hawaii to Tahiti Shuttle Experiment of 1979 and 1980 (Wyrski et al. 1981), four deployments of satellite-tracked buoys were made in the Equatorial Countercurrent of the central Pacific. The results of this work have not yet been published other than in a preliminary report (Patzert and McNally 1980). The buoy trajectories resulting from these deployments have kindly been made available to me by G. J. McNally of the Scripps Institution of Oceanography and are shown in Figure 11.

The buoys were released in the winter of 1979, the summer of 1979, the winter of 1980, and the spring of 1980. In the two winter releases, buoys drifting eastward in the Countercurrent did not reach long. 140°W before recirculating into the North Equatorial Current. In the summer release of 1979, recirculation into the North Equatorial Current occurred east of long. 120°W . In the spring release of 1980, the extent of the eastward drift was not determined before observations were terminated. Most of the buoys drifted past long. 120°W and two buoys drifted eastward of long. 110°W .

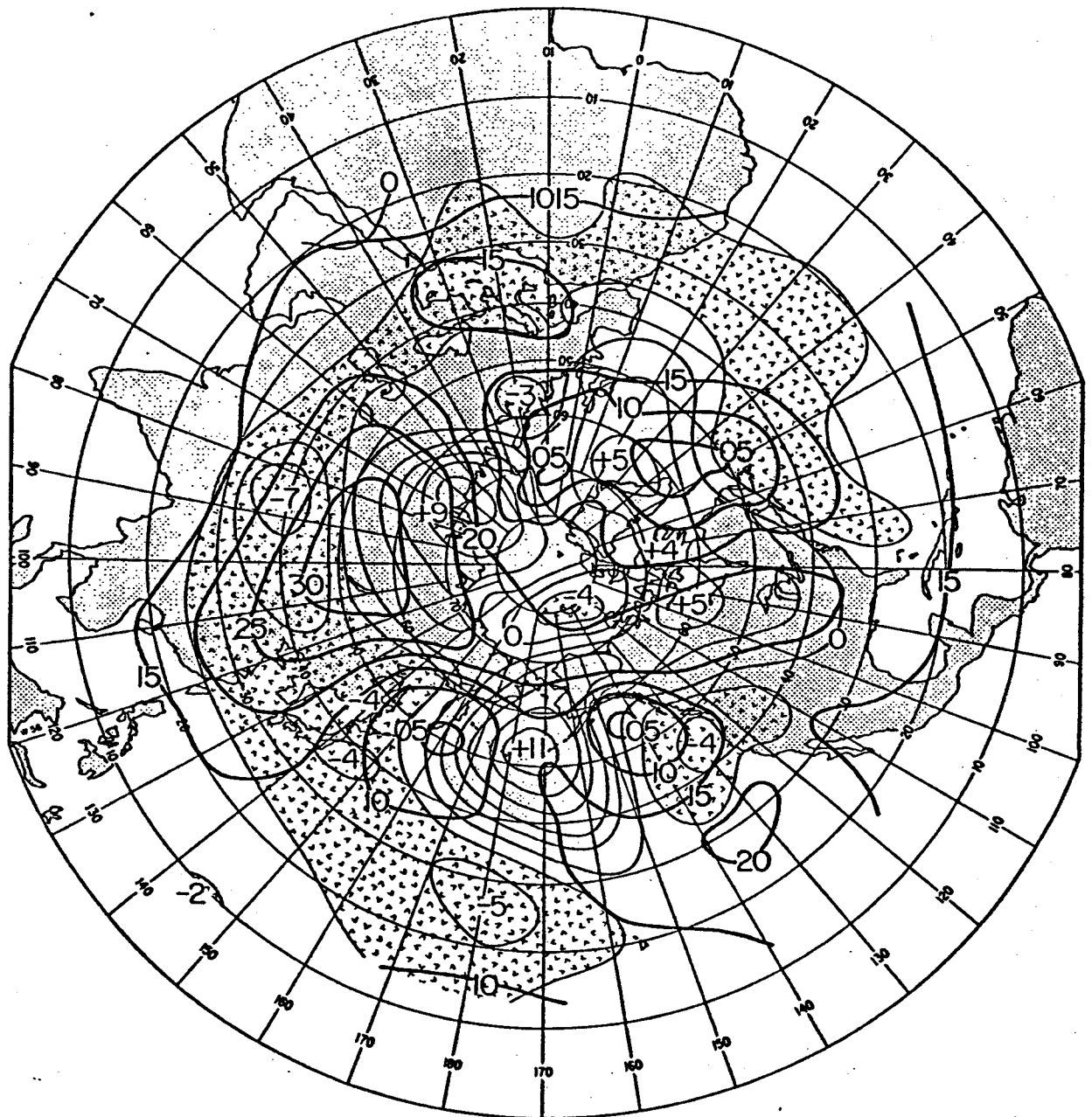
Oceanographers have long been aware of the annual variation in the flow of the Equatorial Countercurrent. The results of this drifter experiment, however, for the first time, show the clear-cut annual variation in the eastern extent of the Equatorial Countercurrent. These results may have pertinence to questions of tuna migration and distribution. For application to the debris drift problem, the results are a good illustration of how the paths of drifting objects are affected by annual variations in not only the speed, but also, the extent of ocean currents.

Finally, Wyrski (1974) used tide station data from islands in the tropical Pacific to derive indices of current speeds. Time series of these indices for the equatorial currents are reproduced in Figure 12. The time series show that large annual and interannual variations occur in the North and South Equatorial Currents as well as in the Equatorial Countercurrent.



CONTOUR INTERVAL 5mb

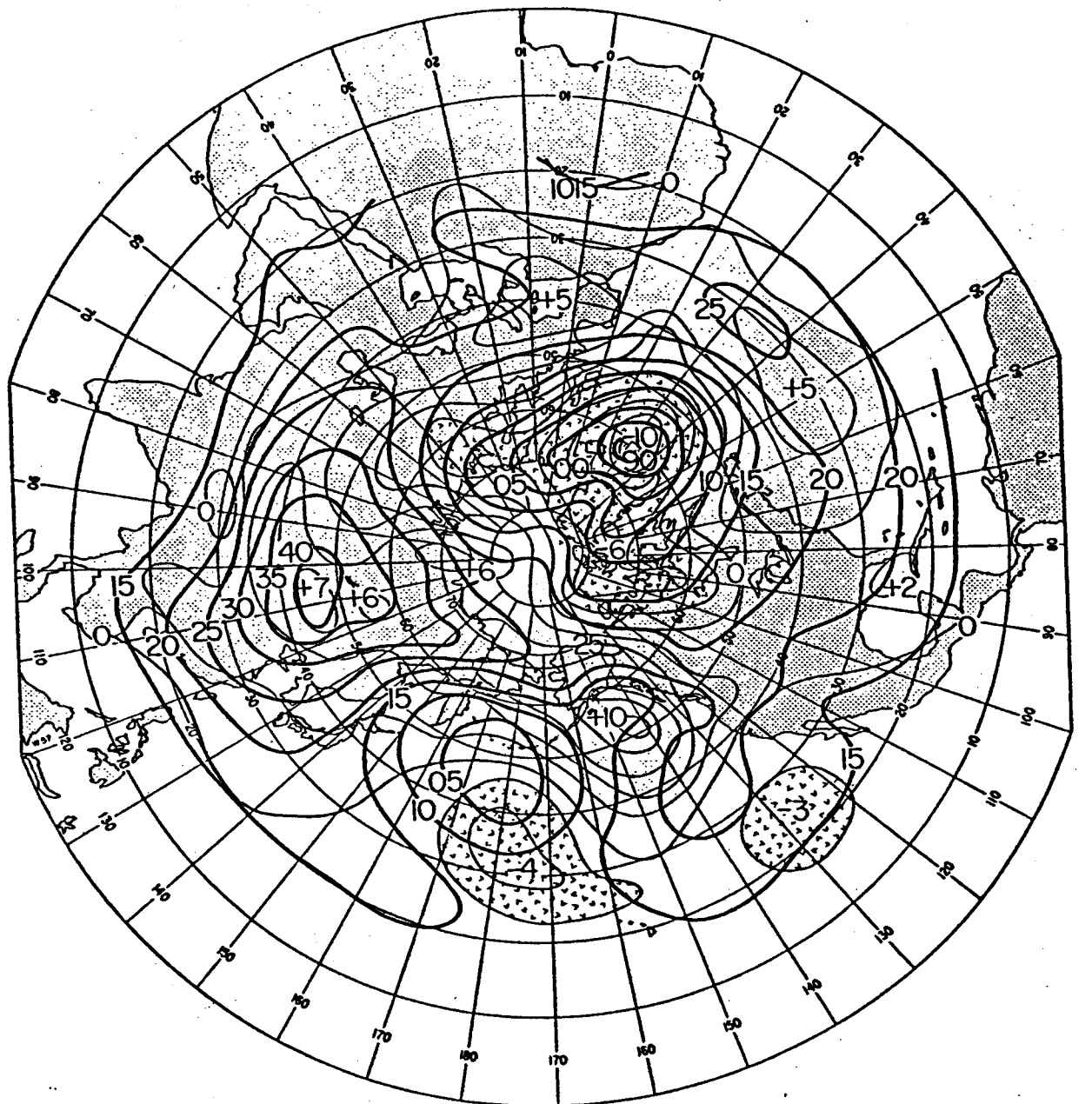
Figure 10a.--Sea level pressure, 26-year mean, winter 1947-72. The Aleutian Low is the area of lowest pressure over the mid-latitude North Pacific (Namias 1975).



CONTOUR INTERVAL 5mb
CONTOUR INTERVAL 2mb

— SEA LEVEL PRESSURE
— DEPARTURE FROM 26-YEAR MEAN

Figure 10b.--Mean sea level pressure, winter 1955-56 (Namias 1975).



CONTOUR INTERVAL 5mb
CONTOUR INTERVAL 2mb

— SEA LEVEL PRESSURE
- - - DEPARTURE FROM 26-YEAR MEAN

Figure 10c.--Mean sea level pressure, winter 1956-57 (Namias 1975).

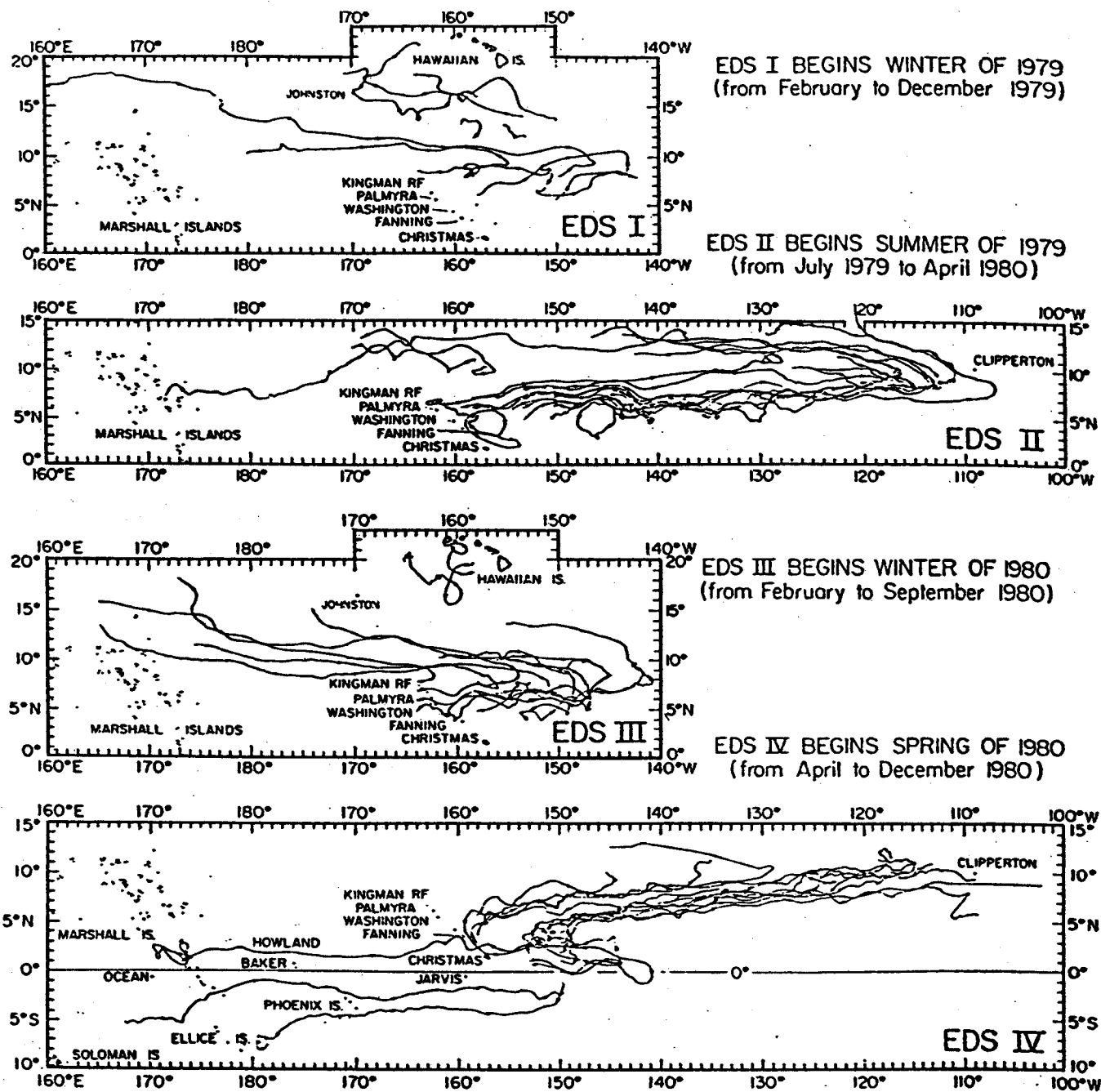


Figure 11.--Composite plots of the final trajectories obtained from four groups of satellite-tracked buoys deployed during the NORPAX Hawaii to Tahiti Shuttle Experiment, February 1979 to December 1980 (McNally pers. commun.).

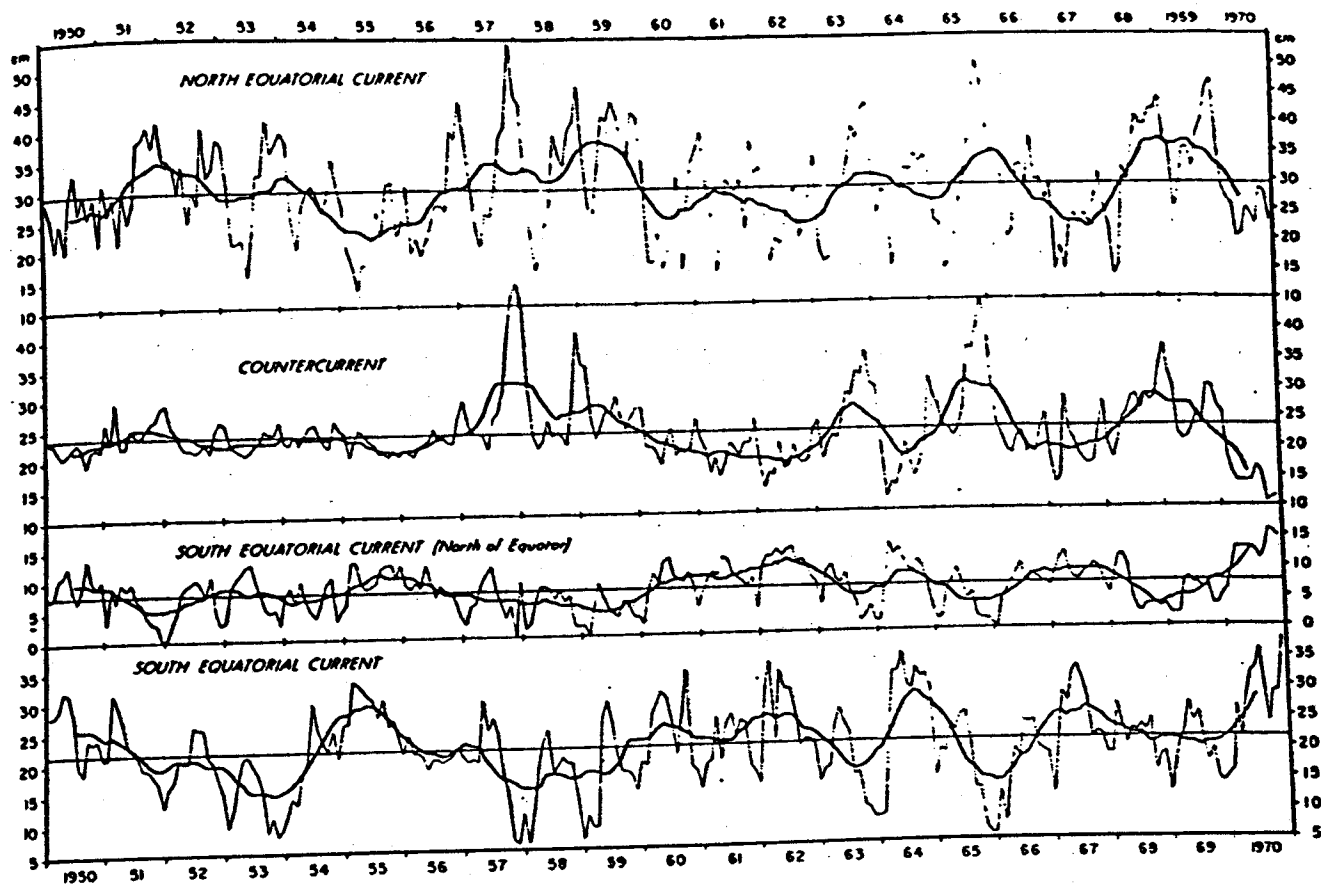


Figure 12.--Time series of sea level difference (in centimeters) across zonal currents of the western central equatorial Pacific, 1950-70 (Wyrтки 1974).

MORE ON SHIP DRIFT OBSERVATIONS

Before leaving the description of ocean currents, it should be pointed out that the first method used to map ocean currents, namely the ship-drift method, is by no means obsolete. Satellite navigation together with an accurate knowledge of ship speed and direction permits more frequent and reliable determinations of ship-drift than was possible during the days of celestial navigation. Figure 13 shows an example of ship-drift determinations made by NOAA Corps Officer Craig Nelson on NOAA ship Townsend Cromwell while traveling from Hawaii southeastward to the equatorial region. Although Officer Nelson had doubts about the accuracy of the ship's speed, a westward component of drift was determined in the North Equatorial Current, an eastward component of drift in the Equatorial Countercurrent, and again, a westward component of drift in the South Equatorial Current. Ship-drift data, from heavily traveled shipping lanes crossing major ocean currents, can provide valuable information about the temporal variability of current velocities.

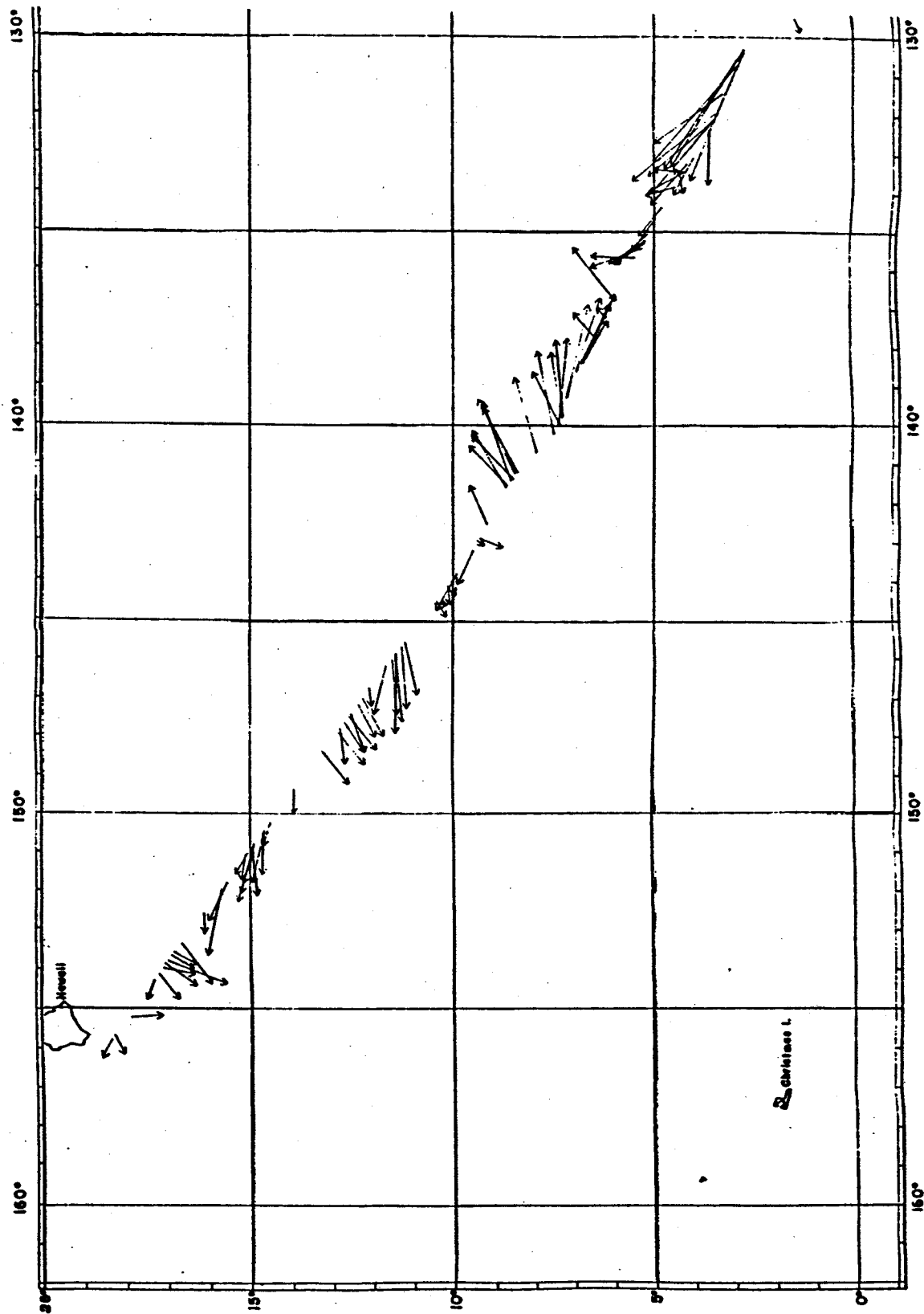


Figure 13.---Shift-drift vectors computed on the NOAA ship Townsend Cromwell using satellite navigation when traveling southeastward from Hawaii to the Equator (Nelson pers. commun.).

CONCLUSION

We have seen how the study of ocean currents has progressed from ship-drift observations to indirect, dynamic calculations and back again to direct measurements by current meters and Lagrangian drifters. During the last two decades, oceanographers have advanced from descriptions of average and steady state ocean currents to descriptions of their variability. Important advances have also been made in our understanding of the effects of atmospheric forcing on ocean currents. It is evident from the examples presented that the prediction of debris paths and destinations will depend not only on a knowledge of the general ocean circulation, but also, on an area-specific understanding of the variability of currents on time scales up to the interannual.

Complicating the prediction of debris paths is the fact that there are all kinds of debris. The satellite-tracked drifting buoy method of monitoring ocean currents provides a good indication of how debris will move in the ocean. Not all debris is as deeply anchored in the water with little exposure to the wind, however, as are the buoys. Debris can consist of plastic floats riding high on the water, partially submerged logs, or floats with fishing gear hanging deep in the water. Therefore, in addition to a knowledge of the water movement, the movement of the floating object induced by the drag of the wind must be considered when predicting debris paths. At this stage, I am happy to pass the problem on to the modeler.

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ON THE GENERAL CIRCULATION IN THE SUBARCTIC PACIFIC

Donald K. Reed and James D. Schumacher
 Pacific Marine Environmental Research Laboratory, NOAA
 Seattle, Washington 98115

ABSTRACT

This work attempts to summarize the major features of surface circulation in the subarctic Pacific (from lat. 40°N to the Bering Strait). Effects of the density distribution (geostrophic flow) and wind drift are considered. The Subarctic Current is a slow, eastward drift between lat. 40° and 50°N; in winter speeds increase about fourfold as a result of strong eastward winds. Speeds in the swifter Kamchatka Current-Oyashio may also be enhanced by winter winds. The Alaskan Stream flows westward along the Alaska Peninsula and Aleutian Islands at peak speeds in excess of 100 cm/s, but it does not seem to have any large seasonal variation. Coastal currents off Oregon-Washington generally reverse with a reversal in the seasonal winds. Off southeast Alaska, the northward coastal currents are enhanced by winter winds. The coastal Kenai Current on the west side of the Gulf of Alaska increases in speed from about 25 to 100 cm/s in the fall as a result of a maximum in freshwater discharge. The Kuroshio and Alaskan Stream undergo occasional large interannual variations; the processes in neither system are completely understood, however. El Niño events also produce dramatic changes in water properties (and perhaps currents) along the eastern margin of the North Pacific.

The climatological map of near-surface flow can be used to provide estimates of the movement and transit time of material in the ocean. Off Oregon-Washington and southeast Alaska, winter storms commonly cause shoreward movement that is greater than the alongshore flow.

INTRODUCTION

The task of attempting to summarize the relevant features of the circulation of a large region of the ocean is a rather awesome one. The upper ocean is often rife with eddies and disturbed by large temporal changes, and it is difficult to obtain a firm grasp of the major features of flow for even a limited area from the results of a single survey of a few weeks. When one attempts to use data from many surveys over various seasons and many years, interpretation is subject to numerous sources of

In R. S. Shomura and H. O. Yoshida (editors), Proceedings of the Workshop on the Fate and Impact of Marine Debris, 26-29 November 1984, Honolulu, Hawaii. U.S. Dep. Commer., NOAA Tech. Memo. NMFS, NOAA-TM-NMFS-SWFC-54. 1985.

uncertainty and possible error. Furthermore, the fundamental nature of some of the methods used to infer flow has not in every case undergone rigorous verification. Finally, the presentations of circulations are often incomplete; for instance, effects of wind drift and wave transport are frequently ignored. With these caveats in mind, we will attempt to review the state of knowledge of the circulation of the North Pacific north of about lat. 40°N ; our goal is to emphasize features that would have major effects on the drift of material.

First, we will examine the major types of motion that are generally important components of ocean currents. The climatological mean upper-ocean circulation in the subarctic Pacific is then shown and discussed. An examination of seasonal and interannual perturbations on the mean flow is also attempted. Finally, we highlight certain features of flow that may be especially relevant to the fate of debris in the ocean.

Types of Motion

To clarify much of the discussion to follow, some elementary concepts of the nature of the major kinds of ocean currents will be explained. Those that seem important to us in the context of this presentation are geostrophic flow, wind and wave drift, long waves, and tidal currents.

Geostrophic Flow

Geostrophic (or Earth-turned) flow results from a balance between the density or pressure gradient force and the deflecting force of the Earth's rotation. No actual statement is made about whether flow results from the density distribution or the density field results from the flow. In general though, we consider the density field to result from unequal cooling and heating, variable freshwater input, and the large-scale stress of the winds. The requirements for pure geostrophic flow are quite restrictive (a steady state, straight-line flow, no friction, and no change in flow along its path (McLellan 1965)), but many recent comparisons indicate that flow below the wind-mixed upper layer is generally at least quasi-geostrophic (within a few percent of an exact force balance). Hence, geostrophic flow calculations are a powerful tool, and they can be based on the very large data set of hydrocasts (conductivity-temperature-depth and Nansen bottle casts) built up over decades. Furthermore, the calculations often appear to be valid even in relatively shallow water (Schumacher and Kinder 1983), and intermediate reference levels (1,000 and 1,500 m) in the deep ocean in the northern Pacific seem to result in only slight deficiencies in speed (Reid and Arthur 1975). Much of the information presented below is based on use of the geostrophic relation.

Wind and Wave Drift

The direct action of wind stress on the sea surface produces currents; in addition, waves also form, and they in turn have a residual velocity in the direction of the wave train as a result of the fact that the particle orbits decrease in size with depth (Pond and Pickard 1978, for example). This wind drift (Ekman flow) and wave drift (Stokes drift) may result in appreciable speeds in the upper 50 m or so during times of strong winds. A schematic representation of the possible combined effects of geostrophic flow, wind drift, and wave drift is given in Figure 1. It appears that

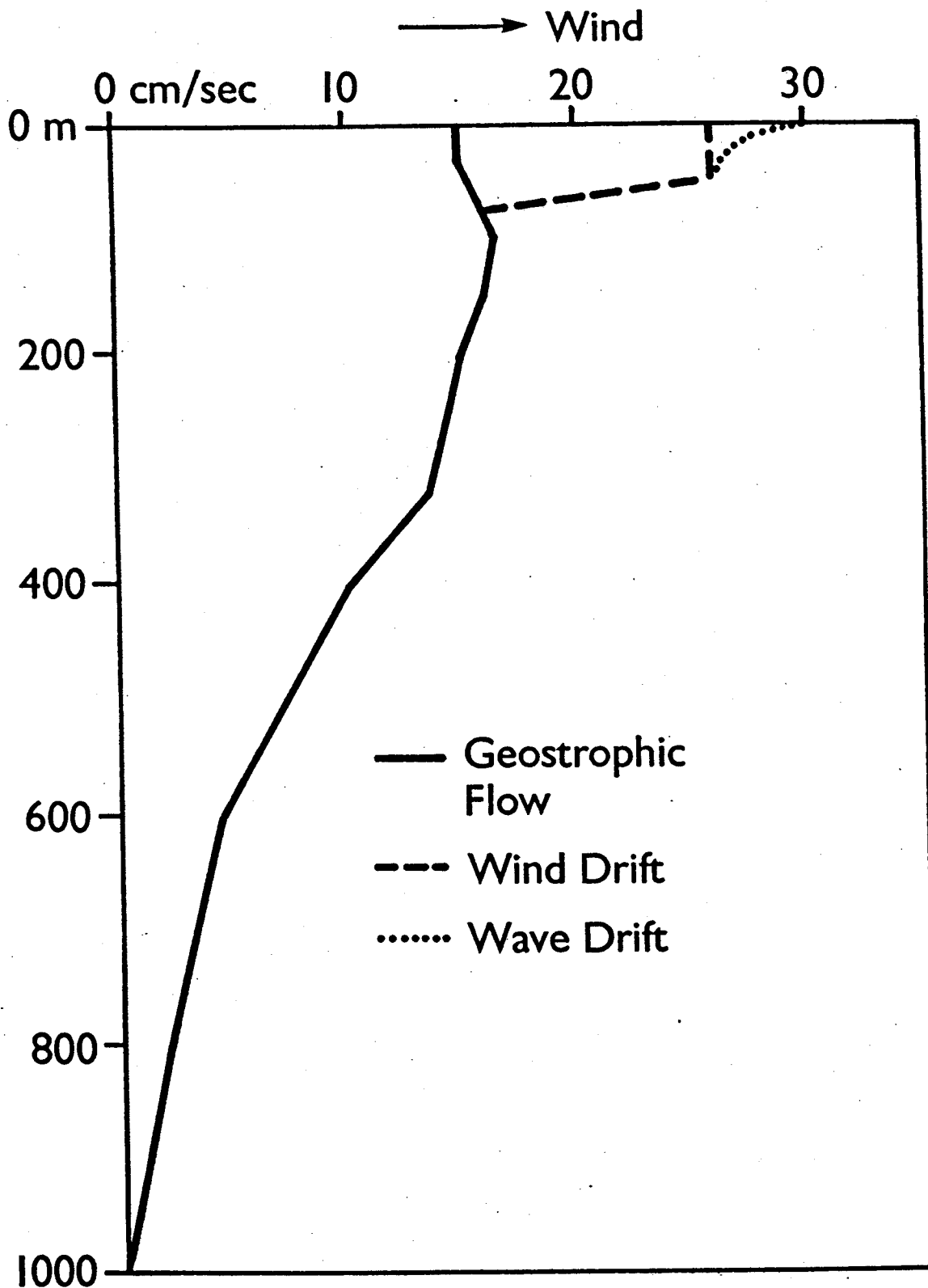


Figure 1.--Representative example of the combined effects of geostrophic flow, wind drift, and wave drift.

"Ekman spirals" (surface current 45° to the right of the wind, with velocity decreasing and turning clockwise with depth) seldom obtain in the real ocean, and the combined effects of wind and wave drift seem to produce a flow of nearly constant direction which does not diminish greatly until near the bottom of the mixed layer (James 1966; McNally 1981). Precise measurements of the exact behavior of wind and wave drift are very hard to make because of the difficulty of separating the components and eliminating the effects of other flows. McNally (1981) analyzed a large set of drifter data which suggests that the upper 30 m moved at about 1.5% of the wind speed at 20° to the right of the wind direction. This approximation is used here.

Long Waves

The long waves examined here are planetary waves and Kelvin waves. Other types of long waves exist but are, except for tidal currents discussed below, not believed to be of general importance to the problems to be dealt with. Although it may be an oversimplification, planetary waves may be thought of as highly curved ocean currents that result from interactions with bottom topography or from strong velocity shear. Some of the observed variability in thermal and density structure results from these features, especially in the subtropical gyre (Magaard 1983). Planetary waves seem to be prevalent in the Kuroshio but are not common features of the Alaskan Stream (Reed and Schumacher 1984). Since we cannot properly specify them and their effects on surface flow, they will not be dealt with further. Kelvin waves are long boundary waves (near a coastline or the Equator) that are often initiated by large changes in the wind (Voorhis et al. 1984). They are quite important along the Equator and appear to be a major factor in the initiation of El Nino events and their poleward spreading (Wyrski 1975). Thus, some of the large interannual changes seen in the subarctic Pacific are linked to these waves.

Tidal Currents

Currents associated with the rise and fall of the tide are typically only ca. 2 cm/s in the deep ocean but can easily be 20 cm/s in water depths of 100 m (Dietrich 1963). Hence, they are of no importance to processes such as larval drift in the open ocean, but their relatively high velocities in shallow water make them a critical factor for the movement of material in the nearshore environment.

Climatological Mean Circulation

Figure 2 shows the paths of a number of drifting buoys from a study by McNally et al. (1983); the data are not examined in detail here, and the figure is only meant as an aid to orient the viewer to the larger-scale features of the North Pacific near-surface circulation. Note the Kuroshio and its eastward flow, which forms the northern boundary of the subtropical gyre, and the North Equatorial Current and the countercurrent to the south. The Subarctic Current and flow into the Gulf of Alaska are also shown. Figure 3 shows the tracks of drifters (Reed 1980) that were deployed in the Alaskan Stream but followed zones of recirculation south into the Subarctic Current and back into the Gulf of Alaska. One drifter moved into the coastal Kenai Current. We will concentrate below on features of the subarctic circulation.

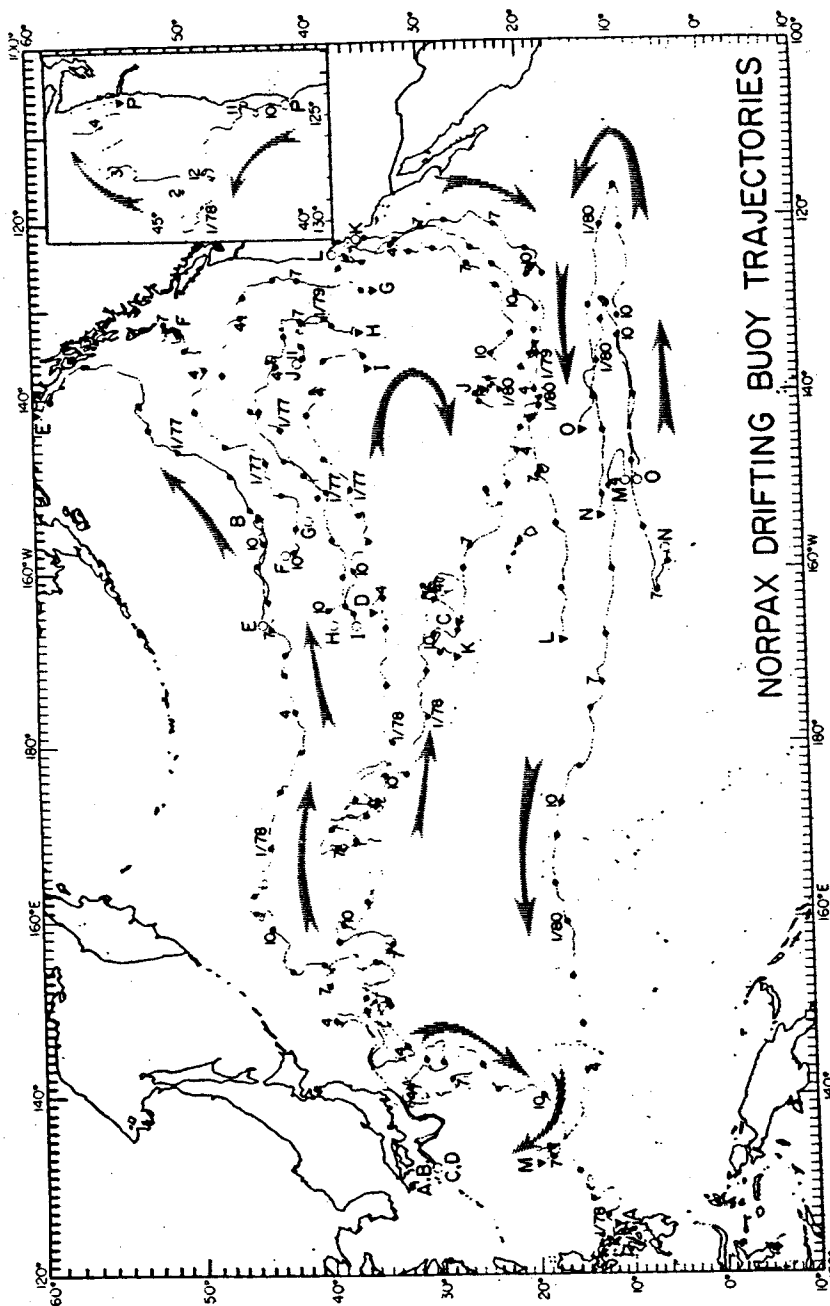


Figure 2.--Trajectories of drifting buoys in the North Pacific from McNally et al. (1983) during 1976-80. Solid circles indicate the first day of each month.

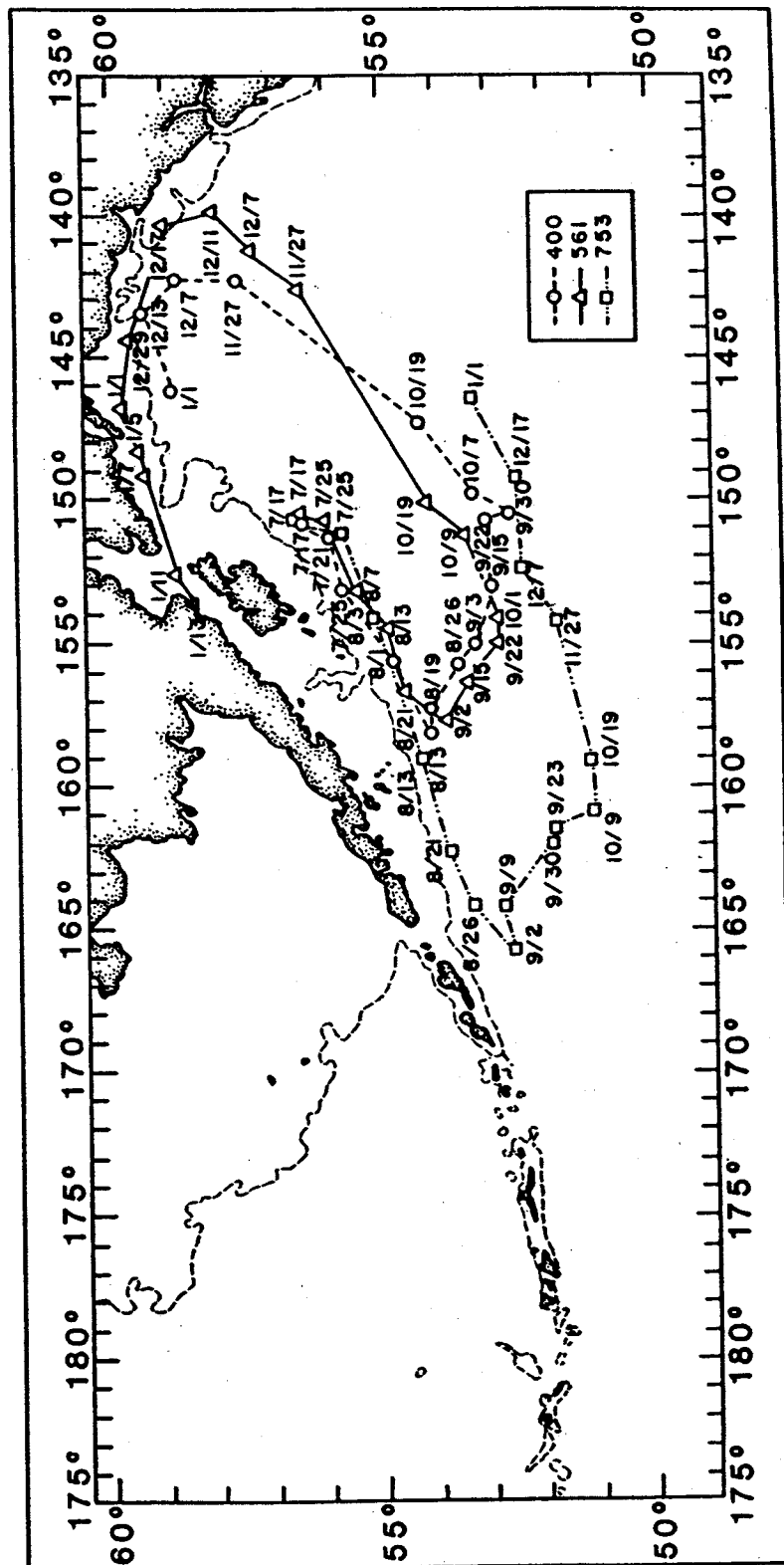


Figure 3.--Paths of drifting buoys indicating near-surface circulation around the Gulf of Alaska gyre (from Reed 1980), July 1978-January 1979.

Figure 4 is our attempt to present the climatological mean surface circulation of the subarctic Pacific. It is based on previous presentations of geostrophic flow (such as Dodimead et al. 1963; Reid and Arthur 1975; Reed 1984) and the results of drifting buoys and other direct current measurements (Reed 1980; Schumacher and Reed 1980; McNally 1981; McNally et al. 1983; Schumacher and Kinder 1983). Since the contribution of wind drift has been included, it should represent the expected total current better in some areas than geostrophic computations alone. The speed values shown on the figure are estimates of representative values; in the swifter currents, individual peak speeds would at times exceed those shown, but spatial averages across the flows would likely be smaller. In the broader, slower currents the values should be close to spatial averages. Certain features of coastal currents with known temporal variation are not shown but are discussed below.

The swiftest flow shown is in the Kuroshio, but peak speeds in the Alaskan Stream (Reed 1984) are at least half those off Japan. The Kuroshio extension retains appreciable speeds, but the mixture of this water and that from the Oyashio, which is known as the Subarctic Current, is much broader and slower. The Subarctic Current is probably more affected by wind drift than any other flow in this region; geostrophic speeds are usually <5 cm/s, but winds blow in the direction of this flow and considerably augment it, especially in winter (McNally et al. 1983). The Subarctic Current diverges off the U.S. west coast, typically off Vancouver Island, and a portion flows south as the California Current, which is generally opposed by the winter winds. (Inshore of the California Current, a northward flow, the Davidson Current, is usually present in winter.) The remainder of the Subarctic Current turns northward into the Gulf of Alaska; as this flow leaves the head of the Gulf of Alaska, it deepens, narrows, and intensifies. This westward outflow is known as the Alaskan Stream (Favorite 1967), and it continues westward along the Aleutian Islands until it enters the Bering Sea near long. 170°E . There is a separate coastal current inshore of the Alaskan Stream; this Kenai Current (Schumacher and Reed 1980; Royer 1981) extends from at least Prince William Sound, along the Alaska Peninsula, and through Unimak Pass into the Bering Sea. The weak extension of this flow in the Bering Sea closely parallels the 50-m isobath (Schumacher and Kinder 1983). The water entering the Bering Sea from the Alaskan Stream appears to flow mainly along the continental slope in the western part of the Bering Sea; the flow turns south off Kamchatka and forms the Oyashio, which reaches northern Japan.

Seasonal Variations

Knowledge of seasonal variations in currents in the subarctic has only come recently, mainly as a result of direct current measurements. Table 1 is our assessment of some of the likely seasonal effects; as more information is accumulated, this estimate will need to be revised. The two swiftest flows (the Kuroshio and Alaskan Stream) are not listed. Transport of the Kuroshio does appear to increase by 10-15% in summer (Blaha and Reed 1982), but interannual changes are much larger. It is not clear if the Alaskan Stream has a seasonal signal, but again obvious interannual changes sometimes occur (Reed 1984). The Subarctic Current (Table 1) clearly is strongest in winter (Reed 1980; McNally et al. 1983); the geostrophic flow is about 5 cm/s all year, but strong winter winds appreciably augment the

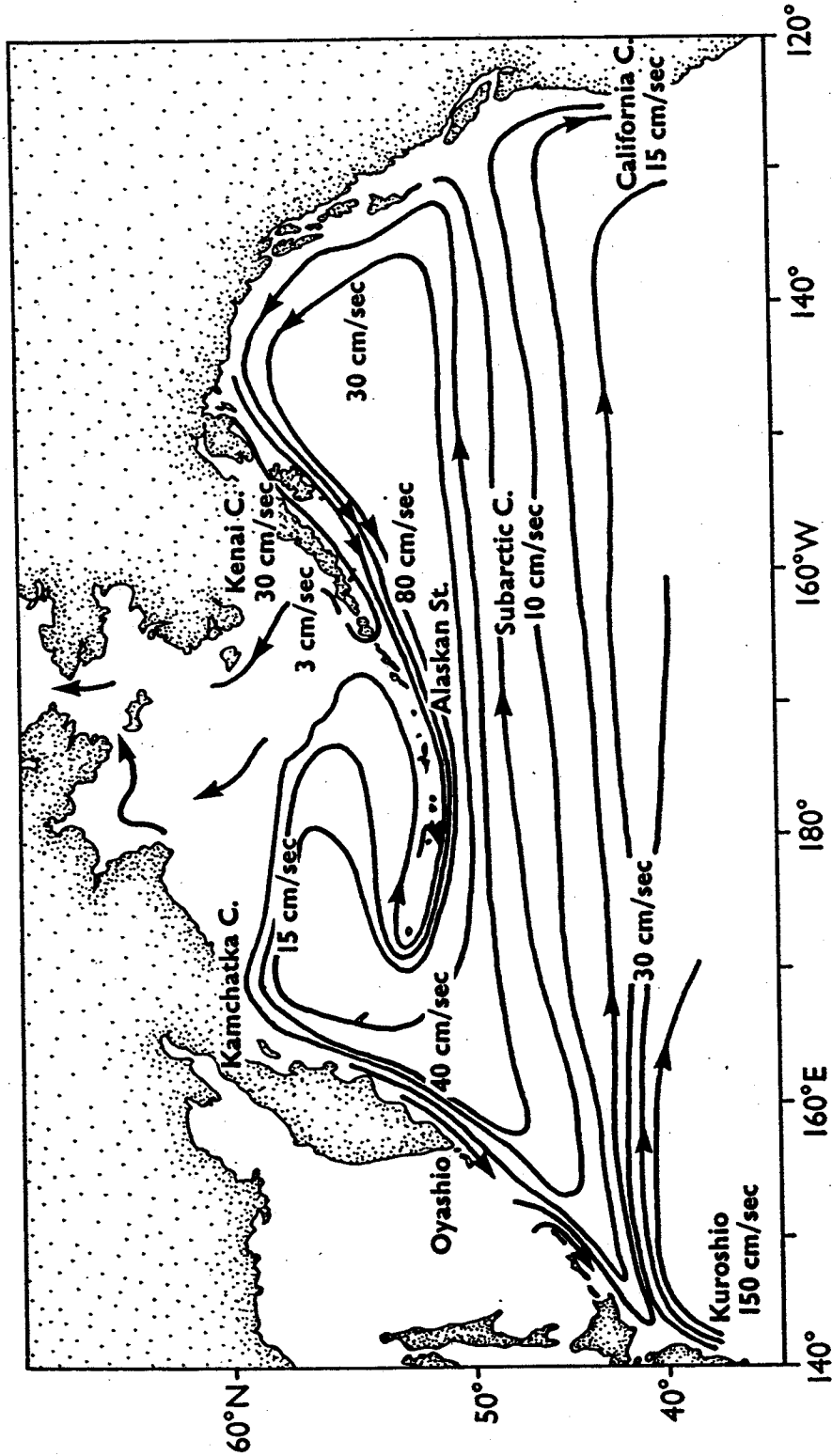


Figure 4.--Estimates of the climatological mean surface circulation in the subarctic Pacific.

Table 1.--Estimates of the seasonal variation in various surface current regimes in the subarctic Pacific.

Current or region	Time	Minimum		Maximum		
		flow speed (cm/s)	Direction	Time	flow speed (cm/s)	Direction
Subarctic Current (lat. 40°-50°N)	Summer	5	East	Winter	20	East
Kamchatka Current	Summer	30	Southward	Winter	50	Southward
Bering Sea (flow along 50-m isobath)	Summer	2	Variable	Winter	4	Variable
Kenai Current	Winter, spring, summer	25	Southwest	Fall	75	Southwest
Alaska, southeast coastal	Summer	10	Northward	Winter	20	Northward
Oregon-Washington coasts	Spring-summer	20	South	Winter	20	North

flow in the mixed layer. The Kamchatka Current probably has significant wind drift southward in winter. Reid (1973) concluded that this current has increased baroclinic structure and geostrophic flow in winter, but Ohtani (1970) casts doubt on this being a large-scale general feature of the flow.

The remainder of this section deals with coastal currents. In the eastern Bering Sea, the coastal flow along the 50-m isobath appears to have greater speeds in winter than summer (Schumacher and Kinder 1983), presumably through some action of the winds. In this and other areas of the shallow Bering Sea, intermittent ice melt in winter may also provide localized, occasional sources of buoyancy that enhance geostrophic flow. The Kenai Current undergoes a relatively large and rapid increase in speed in the fall (usually October); this change is not mainly produced by winds but is the result of a dramatic increase in freshwater drainage at this time (Schumacher and Reed 1980; Royer 1981). In the coastal waters of southeast Alaska, direct current measurements and sea level suggest an increase in northward speeds in winter (Lagerloef et al. 1981; Reed and Schumacher 1981), probably as a result of persistent winds from the south. Coastal currents off Oregon and Washington also seem to change seasonally;

ly southward in spring and summer in conjunction with g, but a northward flow (the Davidson Current) exists in Smith 1983). Some of these changes probably result from , but the large-scale winds and alongshore pressure also be important (Hickey 1981).

Annual Variations

By interannual variations, we mean changes that occur intermittently; some of them may happen most often in one season, but they do not occur every year. The Kuroshio path undergoes large changes every few years; one mode is relatively straight flow along the coast of Japan, and the other is a large offshore meander (Taft 1972). Changes in speed and transport also seem to occur, but variations in relation to mechanisms may not have been completely resolved. Recent data (Reed 1984) have revealed an interannual change in speed and transport of the eastern part of the Alaskan Stream as shown in Figure 5. In February-March 1980 the source waters of the stream had all entered the head of the Gulf of Alaska, and peak speeds were about 100 cm/s. In August-September 1981 about half of the source water entered the stream between long. 150° and 165°W; peak speeds to the east were only about 50 cm/s, but values along the Aleutians were similar during the two cruises. It was suggested (Reed 1984) that this large-scale change, which is not entirely seasonal, resulted from the effects of differential vertical displacement of the pycnocline caused by an unusual distribution of wind-stress curl in the region of the inflowing source waters.

At least one other interannual event is of importance to the subarctic Pacific: the El Niño phenomenon. Marked changes in water temperature and sea level may occur all along the eastern margin of the Pacific and into the Gulf of Alaska (Enfield and Allen 1980), and these anomalies are presumably accompanied by some changes in currents. Cannon et al. (in press) concluded that since about 1920 the El Niño events of 1941, 1958, and 1982 have produced major changes as far north as the Gulf of Alaska; the large tropical El Niño of 1972 did not cause large anomalies north of California, however. Some of these changes appear to be caused by anomalous northward flow (Smith and Huyer 1983) associated with a long wave propagating from the Equator, but drifter tracks in winter 1982-83 suggest that the process was also aided by anomalously strong northward wind drift (T. C. Royer pers. commun.). The effects of El Niño events may be felt from southern California to the Gulf of Alaska, and even into the Bering Sea, for a distance of about 300 km off the coast, but elsewhere the effects seem to be much less marked. This process may affect the drift of material as a result of the anomalous currents produced.

Inferences on the Fate of Debris

For assessing the likely movement of material on the surface of the ocean, one would like an actual current forecast similar to weather forecasts. In the absence of such information, climatological information (Fig. 4) can be useful. For example, if an object entered the ocean off northern Japan, it should arrive off the U.S. west coast about 2 years later. If the object extended above the water, direct windage effects might appreciably lessen this time. As another example, assume that material entered the Kenai Current near long. 150°W. About 40 days later,

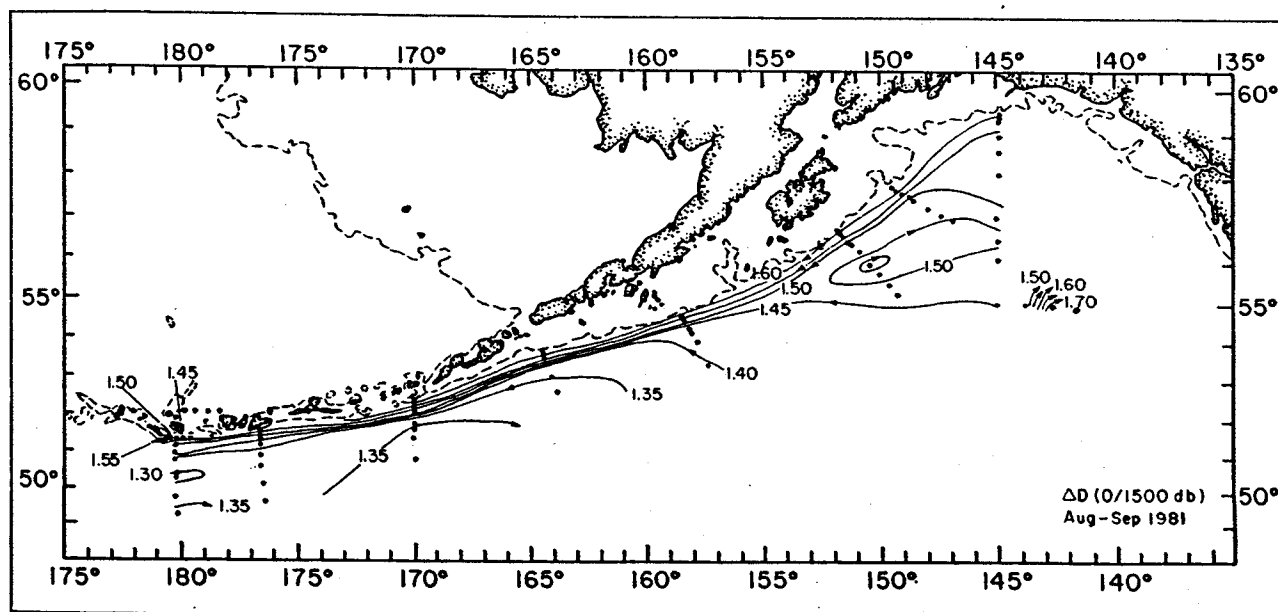
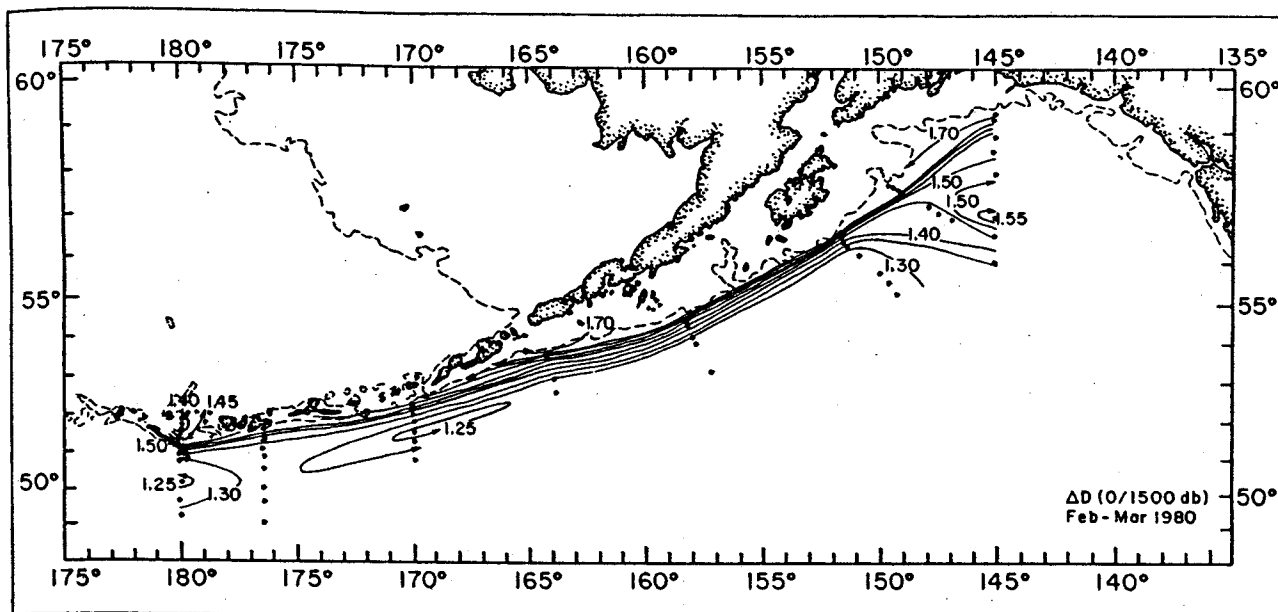


Figure 5.--Geopotential topography (in dyn m) of the sea surface, referred to 1,500 db, February-March 1980 and August-September 1981 (from Reed 1984).

Unimak Pass at long. 165°W; during the fall velocity transit this distance in about 15 days.

enters the nearshore environment, climatological data must be used with considerable caution. Waters that move alongshore may be transported toward shore by a storm of any type. For example, this is apt to happen in winter off Oregon and Washington, where material is frequently driven onshore and litters the beach. Water velocities associated with strong winds probably exceed 30 cm/s, which is greater than the typical alongshore velocities. Thus, material moving east in the southern part of the Subarctic Current may continue south in the California Current or be driven ashore, mainly depending on local weather conditions. Similar processes occur along the coast off southeast Alaska. Finally, tidal currents may play a role in coastal waters, where water displacements during half a tidal cycle are typically about 5 km (Dietrich 1963). Thus, material may be transported into bays or estuaries at times.

Currents that affect the drift of material are quite variable in space and time. One seldom has adequate information to make reliable diagnostic predictions of trajectories. Models are useful, however, because probability can supplement the limited deterministic information.

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OCEANOGRAPHIC FACTORS AFFECTING THE PREDICTABILITY
OF DRIFTING OBJECTS AT SEA

Jerry A. Galt

Office of Oceanography and Marine Services, NOAA
Seattle, Washington 98115

ABSTRACT

Movement within the oceans is turbulent. One of the obvious implications of this statement is that there is a random or uncertain character to the path that any particle may take. This suggests that, although the most probable or mean path of a floating object may be well defined by the most probable or mean currents, there is error or uncertainty that is associated with the predicted particle trajectories. This paper will discuss the relationships between oceanographic processes and this uncertainty.

The path of a floating object can be thought of as a Lagrangian trajectory. Its buoyancy imposes an important constraint and limits its motions to the special subset of two-dimensional movement. Two-dimensional surface motion (even random or turbulent) is subject to the kinematic constraints associated with the incompressibility of water. This means that any vertical motion of the upper layers of the ocean must be coupled to a corresponding convergence or divergence of the surface currents. Convergences act to collect or concentrate floating particles (antispreading or reduced uncertainty); whereas divergences will act to scatter and spread out floating particles. As a familiar example, the small-scale foam lines and "tide rips" seen in coastal waters represent strong collection or processes where the vertical water movement in the surface layer totally dominates diffusive or turbulent scattering processes. The significance of these processes on the predictability of future flotsam positions is discussed in this paper. A number of oceanographic processes can potentially contribute to the convergence or divergence of the surface currents. On the largest midocean scales the curl of the wind stress field and Rossby waves contribute to these processes. Both of these processes typically have strong signatures in the baroclinic temperature and salinity fields; the use of these signatures as factors in predicting trajectories is considered. On the smaller scale of the continental shelf, the effects of variable bathymetry can become important in the prediction problem. Even closer to shore, coastline configuration, freshwater runoff and tidal currents can all become important mechanisms. Each of these mechanisms is discussed.

INTRODUCTION

For ages people have gone to beaches and found flotsam that has traveled possibly over truly global distances to arrive at some particular spot. Glass ball floats found along the Pacific coast of the U.S. are one example; driftwood found along the Arctic coast of Alaska is another. Anyone who has spent time at sea knows that drift can be puzzling, even on local scales. For example, where is the buoy that came loose during the night, or for that matter, what are the odds of successful recovery during a man overboard drill in rough seas? On even smaller scales, sewer outfalls deliver material into the ocean or into the marine environment with the absolute conviction that it will be lost and not accumulate in the vicinity at which it was injected into the system.

Mobility of the ocean surface is obvious to any observer. Mixing and moving are clearly operating over a wide range of time and length scales. Trajectory analysis is the intent to determine particle pathways which account for all of this movement and spreading. This type of analysis can be considered from a source point of view (i.e., something entered the water here, and one would like to know where it will be as time goes on), or from what is known as a receptor point of view (i.e., this is the spot where something was found, and I would like to know where it came from, and how long it took to get here). In either case it is necessary to know about the various scales of movement and spreading that are found in the ocean.

For the purposes of this paper, I will confine my attention to objects that are buoyant and thus constrained to move with at least some part of their structure at the surface of the ocean. I will also concentrate on trajectories of particles at sea and not consider the processes that affect beaching. I will attempt to go over some of the factors that control the movement of floating objects and the uncertainties surrounding the estimates of this movement.

The next section of this paper will discuss the ways we typically divide movements into currents on the one hand, and mixing or spreading terms on the other. In addition, I will discuss the typical oceanic relationships between advective and diffusive scales. The third section of this paper will cover scaling discussions for a number of oceanographic processes to estimate their influence on spreading, and thus the "findability" of objects adrift on the ocean surface. The final section of this paper will discuss mixed computational and tracking methods for use in trajectory analysis.

MEAN CURRENTS, TURBULENCE, AND UNCERTAINTY

What we think of as average or mean currents clearly depend on what time and space scales we wish to consider. In most cases, the choice is a compromise between what we would like to know and the amount of data that is available. For example, with only flotsam data, we could say that the average or mean currents seem to run from the North Pacific to the Oregon coast (because we find glass ball floats there), or that the coastal currents east of Point Barrow all run from the east (since the driftwood there has its origins in the valley of the Mackenzie), while the currents

to the south and west of Point Barrow all run to the north through the Chukchi Sea (since all the driftwood there has its origin in the Yukon Valley). A little travel up and down the west coast of the U.S. clearly shows that the mean currents exhibit some variance since glass ball floats are widely distributed. Starting from these admittedly simple examples, we would like to consider a more quantitative way of looking at what we call the "mean currents" and its variance. We will then try and see if this quantitative information can be used to make some estimates about the ease of tracking or finding floating objects at sea.

A more or less traditional starting point for midocean current estimates is the geostrophic equations, and what is known as the "dynamic height method of current analysis" (Fomin 1964). When used with average seasonal data, these familiar techniques give the large-scale circulation patterns that are used in most marine atlases and provide the conventional wisdom about which way the water flows. Many of the results presented by authors in this conference are based on this type of analysis. Detailed measurements of water movements and density fields indicate that even when the geostrophic relationships are true, small imbalances can lead to time-dependent changes in the flow, and so-called quasi-geostrophic motions are observed (Pedlosky 1979). These quasi-geostrophic motions can be analyzed as Rossby waves and appear in the atmosphere as the familiar high-low patterns that are seen on weather maps. In the oceans, these are mesoscale eddies, rings, or thermal anomalies such as thought to be responsible for El Niño patterns. On still smaller scales, we find current variations associated with internal waves, windrows, or Langmuir cells, and this nesting of still smaller and smaller scales can go on ad infinitum. In practice, we must draw the line somewhere and make a pragmatic separation in what is really a continuum of scales of motion. In this separation we decide that scales above some certain level will be resolved, and these will be called "currents;" scales below that level will not be resolved and these will be called "turbulence" or "uncertainty." Obviously, one person's turbulence could be another person's currents, and often is. For this work, I will stick to traditional, midocean scales and consider currents to be geostrophically balanced.

Given geostrophic current patterns, what can we do about all the other variations and uncertainties that are left out of our definition? To really answer what they mean, we would have to know what they all mean, which is out of the question. Fortunately, there are some relatively simple models that we can use to represent these uncertainties in a statistical way. One of the easiest to understand and most useful was originally proposed by Einstein while he was working on studies of Brownian motion (Csanady 1973). This model is based on the idea of a random walk, i.e., that in each successive time step, an object will move in a random step, either north, south, east, or west with a probability of 25% for each option. Statistical analysis shows that after a number of such steps the distribution of possible positions will take on a two-dimensional, Gaussian shape, and if one were to repeat the experiment with a large number of cases, their cumulative distribution would look exactly like the classical solution to the diffusion equation, or the so-called distribution of variables equation (Sverdrup et al. 1942). This simple conceptual model then provides a framework which allows us to relate uncertainty to the effects seen in turbulence or large-scale eddy diffusion. In the ocean, numerous authors have matched distribution of variables with the

distribution equations and evaluated effective eddy coefficients (Proudman 1953; Defant 1961). This will allow at least an order of magnitude estimate of what the oceanic levels of spreading should be. That is to say, from these coefficients we can go back to the random walk theory and calculate the random mean increase in particle separation and thus establish a relationship between the eddy coefficients, uncertainty, and the average spreading velocity for drifting particles.

To provide a more concrete example, Figures 1a, 1b, 1c, and 1d indicate the results of a series of random walk experiments superimposed on a 1-knot current. In each case, 10 particles were tracked over a period of 100 h, with increasing diffusion velocities (random step size) and correspondingly bigger advective eddy diffusion coefficients or uncertainty values. The values of diffusion coefficients shown here span typical midocean values that are obtained from tide distribution studies. On the low side (Fig. 1a) we see that with a diffusion coefficient of about 10^5 , the corresponding spreading velocities are 0.08 of a knot, and most of the particles would be expected to lie within a circle 10 to 15 nmi after about 4 days of travel. On the high side (Fig. 1d), with a diffusion coefficient of about 5×10^6 , there is an equivalent spreading velocity of about 0.5 knot, and the particles are likely to be scattered over a 40 to 50 nmi circle after 4 days of travel.

Before leaving our simple model for drift calculations we should point out that any floating object will be influenced by surface winds, as well as by the currents. The relative magnitude of this effect will depend on the exposed area and the relative subsurface drag. For the present work, we will consider this to be relatively unimportant with the reservation that in some special cases, the trajectory analysis would be quite wrong if these effects were not included.

From what is presented in Figures 1a-1d, it is seen that even in relatively steady or nonturbulent, midocean regions, the uncertainty associated with the position of a drifting object is likely to increase to a number of miles over the space of a few days. Thus, if the aim is to find an object that is small or offers low visibility, then recovery or tracking will always be difficult. We will now consider a series of oceanographic processes that may counteract the potential spreading of objects and thus may improve the odds of predicting trajectory pathways.

OCEANOGRAPHIC PROCESSES

Any floating object must remain on the surface of the ocean. This constraint imposes an important coupling between the possible surface trajectory pathways that it could take and the vertical velocities in the upper layer of the ocean. Sustained vertical velocities (upwelling or downwelling) have often been identified with anomalous biological activity. They also clearly affect the spreading or concentration of surface waters and, consequently, anything that is floating in them. In the simple, conceptual model that was introduced in the last section one can look at some oceanographic processes that induce vertical velocity, downwelling in particular, and estimate whether they might have a significant effect on the uncertainty of being able to track or locate objects at sea.

20 MILES



DISPLACEMENTS AFTER 100 HOURS
THE CURRENT SPEED IS 1 KNOT
DIFFUSION VELOCITY 0.08 KNOTS
DIFFUSION COEFFICIENT $0.132 \times 10^{-6} \text{ CM}^2/\text{SEC}$

Figure 1a.--Trajectories indicating the path taken by 10 different drifting objects.

20 MILES



DISPLACEMENTS AFTER 100 HOURS
THE CURRENT SPEED IS 1 KNOT
DIFFUSION VELOCITY 0.25 KNOTS
DIFFUSION COEFFICIENT $1.190 \times 10^{-6} \text{ CM}^2/\text{SEC}$

Figure 1c.--Trajectories indicating the path taken by 10 different drifting objects.

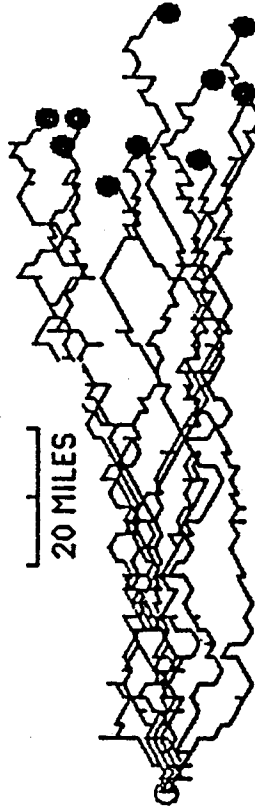
20 MILES



DISPLACEMENTS AFTER 100 HOURS
THE CURRENT SPEED IS 1 KNOT
DIFFUSION VELOCITY 0.17 KNOTS
DIFFUSION COEFFICIENT $0.529 \times 10^{-6} \text{ CM}^2/\text{SEC}$

Figure 1b.--Trajectories indicating the path taken by 10 different drifting objects.

20 MILES



DISPLACEMENTS AFTER 100 HOURS
THE CURRENT SPEED IS 1 KNOT
DIFFUSION VELOCITY 0.50 KNOTS
DIFFUSION COEFFICIENT $4.761 \times 10^{-6} \text{ CM}^2/\text{SEC}$

Figure 1d.--Trajectories indicating the path taken by 10 different drifting objects.

On the largest oceanic scales, vertical velocity is associated with divergences or convergences of the Ekman transport, and this in turn is proportional to the curl of the wind stress. This is represented schematically in Figure 2 where the Ekman convergence tends to depress the thermocline. Major centers of Ekman convergence are associated with midocean gyres. Such places are known to have a tendency on large scales to accumulate floating material. This is clear from the concentrations of sargassum weed in the Sargasso Sea and relatively high concentrations of tarballs found on Bermuda beaches. To get a slightly more quantitative estimate of this effect, it can be seen that the vertical velocity estimates presented by Wyrtki (1961) and Munk (1966) for the bottom of the pycnocline in the Pacific were on the order of 10^{-5} cm/s and discussed in some detail by Overstreet and Rattray (1969). Using this and the geometry shown in Figure 2, a simple calculation shows that the resulting diffusion velocity would be negative, i.e., a convergence rather than a spreading, but that the magnitude of the term would be several orders of magnitude below the point where it would affect the distribution shown in Figure 1a. Thus, this scale of oceanic circulation would have no detectable effect on the spreading of objects at sea.

**Surface layer convergence caused by Ekman flow
proportional to the curl of the wind stress**

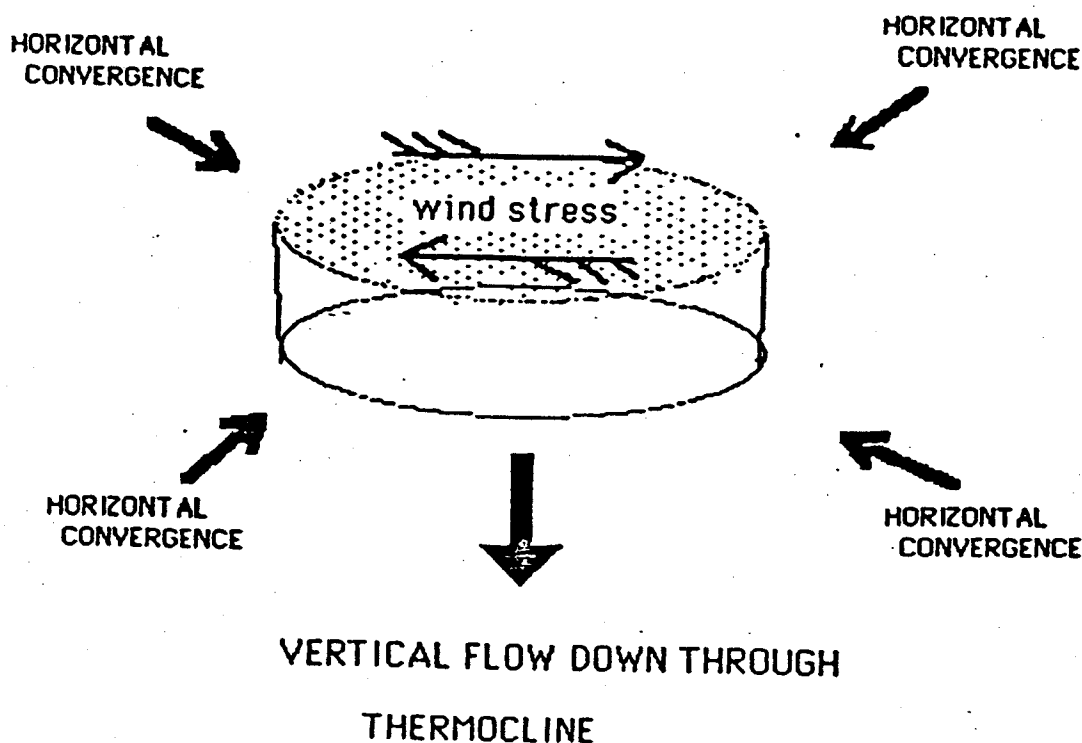


Figure 2.--Schematic representation of convergent Ekman layer as expected in a midocean gyre.

A second large-scale oceanic circulation feature that results in a convergence in the upper layer is the subarctic boundary region in the North Pacific. This permanent feature is well known to Pacific oceanographers and is described in some detail by Reed and Laird (1977). Quantitative estimates of the convergence velocities can be obtained from the work done by Roden (1970) (Fig. 3). From this, we can see that in the vicinity of lat. 40°N , a convergence in the surface currents is evident. Considering that the Ekman drift is confined to the top few tens of meters, this is equivalent to a convergence velocity on the order of 0.1 knot over a north-south line which extends for about 100 nmi. This is obviously a rough estimate, but it indicates that this process is of significant magnitude to affect the lower ranges of spreading we might expect in the open ocean, and several orders of magnitude more important than the convergence associated with the midocean gyres. For higher energy turbulence situations in the ocean, this process is still not likely to

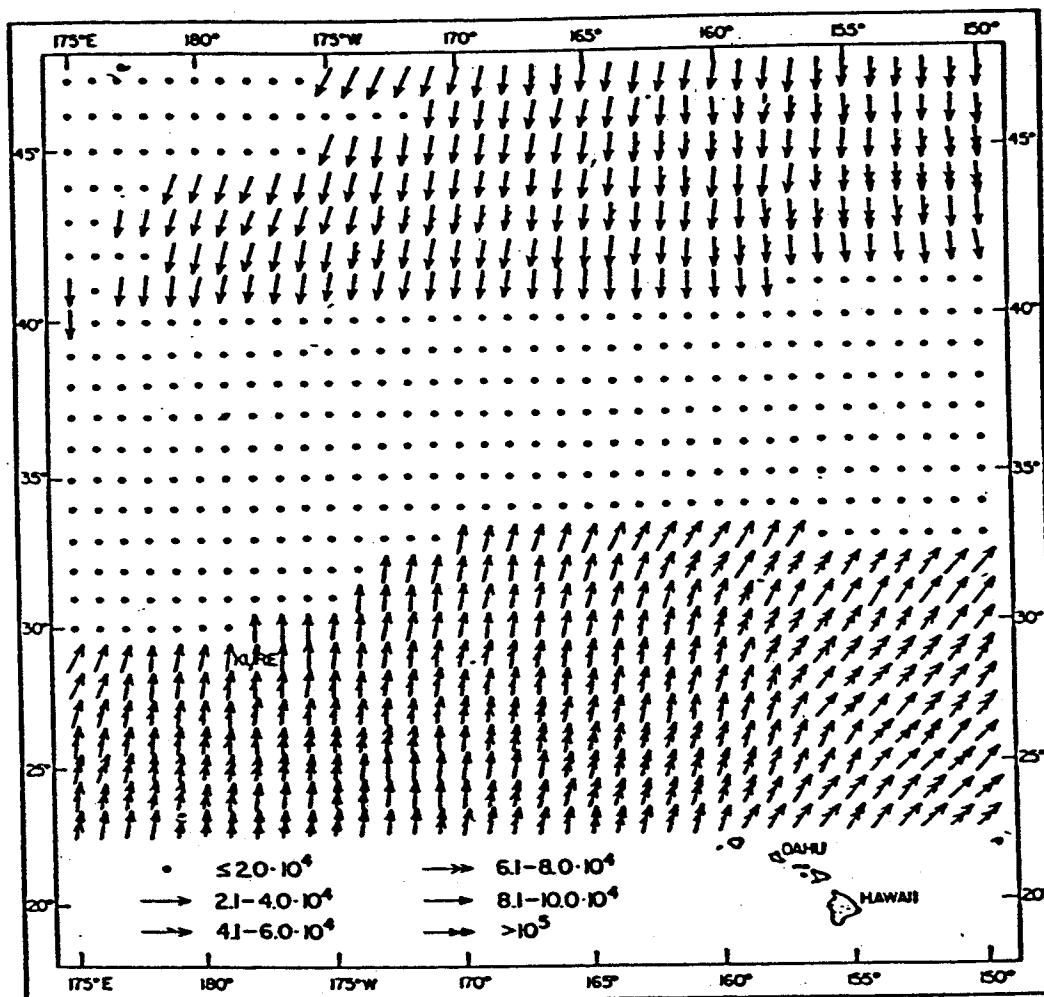


Figure 3.--Surface Ekman transports, in units of $\text{g cm}^{-1} \text{s}^{-1}$, in the central North Pacific. Arrows indicate the direction of transport in April 1968. (Reprinted from Roden 1970.)

significantly improve our ability to make trajectory estimates of drift positions beyond a few days.

The preceding two paragraphs discussed midocean processes. As one encounters the continental shelf, there are additional processes that can induce horizontal convergences that are strong enough to overcome the expected spreading velocities that are associated with typical turbulence estimates. The first such process has to do with bathymetry and the width of the shelf. Geostrophic flows tend to follow bathymetric contours for cases where the baroclinic adjustment is not accomplished such that a level of no-motion is established. A discussion of this process including relevant examples is presented by Galt (1980). Figure 4 indicates the surface circulation over the Fairweather Banks region of the Alaska Continental Shelf. Currents flowing north past Fairweather Banks encounter an abrupt narrowing of the shelf and the current is compressed closer to the shore. The convergent velocities in this case are nearly 0.25 knot. From our previous arguments, we see that these convergences are easily strong enough to make this a region where spreading tendencies would be suppressed, and consequently, the collection of flotsam is likely. Because of the complex shelf topography of the Alaskan coast, many examples of this type of bathymetrically induced collection points can be found.

The continental shelf is a region where freshwater coastal inputs mix with ocean waters of higher salinity to form fronts which provide other regions in which we can expect the possibility of significant convergences. Typically, relatively fresh water will float along the coastline and spread seaward, pushing a narrow mixing front ahead of it as it overrides the more dense seawater. This narrow mixing front is a collection zone that can often totally overcome spreading tendencies. As an example, an oil spill from the grounded tanker Alvenus in August 1984 encountered such a front produced by freshwater runoff from the Mississippi-Atchafalaya drainage basin. After moving nearly 30 nmi, the oil had only spread to a width of 10 m. This is obviously somewhat of an extreme case, but the tendency is general wherever there is significant freshwater coastal currents produced by localized runoff. Many such drainage systems are found in the northeast Pacific, including the winter circulation patterns from the Columbia River and a well-defined flow along the Alaskan Peninsula that has been described by Royer (1981).

In many shelf areas tidal flow can interact with bathymetry and produce horizontal currents. The convergences associated with these flows tend to be the strongest around the mouth of shallow submarine canyons or at the head of dredged channels. These can form the strongest convergences ever observed in the marine environment, and in such cases may totally dominate the horizontal spreading. In one study near the head of Monterey Canyon, drogues that were initially deployed over a several-mile area within a few hours ended up in an area some 10 m across (W. Broenkow pers. commun. 1974). In this case, the convergent velocities completely dominated the spreading velocities. In small harbors (e.g., Baltimore), actual maelstroms have been observed with a core pressure drop equivalent to 5 to 10 cm of water. Incoming tidal waves can override less saline estuarine waters and produce strong convergence lines (so-called "riptides") which typically collect flotsam. These are commonly observed in most of the large estuaries around the northeast Pacific. By their

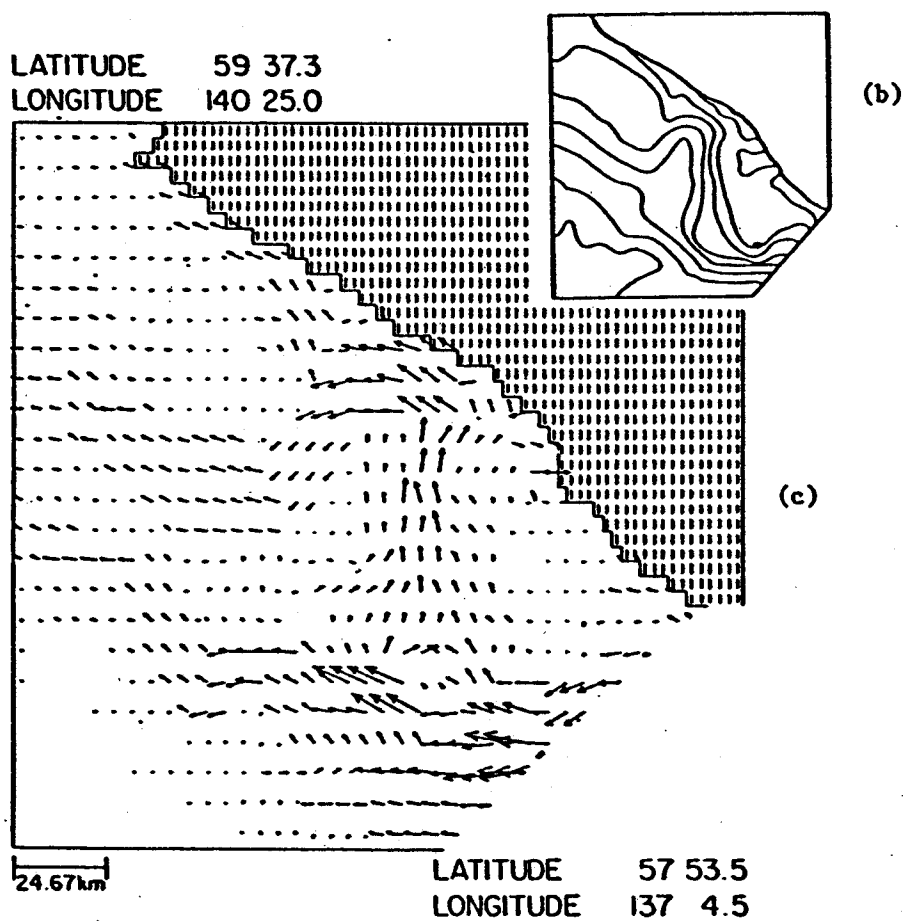
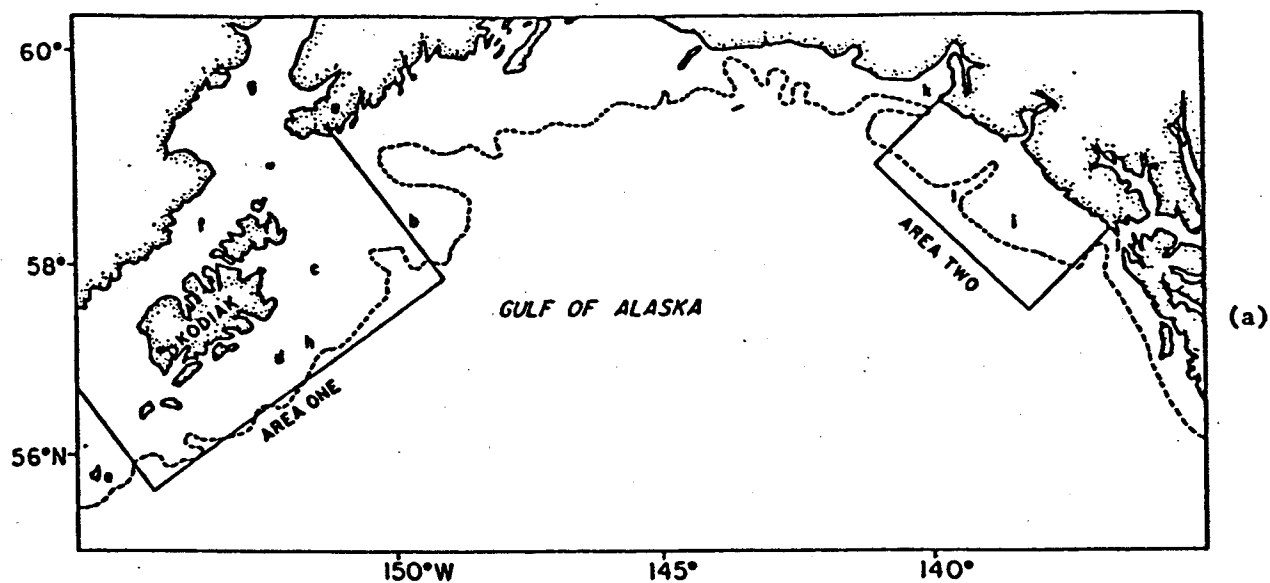


Figure 4.--(a) Area two indicates Fairweather Banks study region, (b) representation of surface elevation or geopotential contours over the Fairweather Banks study region, and (c) surface current pattern for Fairweather Banks study region.

nature, these intense processes can only be present over a part of a tidal cycle and only occur nearshore where large bathymetric variations are present.

SUMMARY AND CONCLUSIONS

Particle or flotsam trajectories can be calculated from water movements. In virtually all cases, the complete details of the water movement and the currents are pragmatically divided into a deterministic, known, and often considered steady portion, and an "everything else" term. The everything else term is usually assumed to have random properties and based on this, a simple statistical model can be developed that introduces the concept of spreading velocity that has the effect of increasing the uncertainty associated with predicting where a particle may end up. A number of oceanographic processes that result in surface convergence were discussed. For each of these cases, the tendency of the convergence velocity to counter the spreading velocity was quantitatively examined. For open-ocean processes, we find that the subtropical gyres have virtually no significant effect on spreading over length scales of hundreds of miles or a few days. The subarctic front in the North Pacific may marginally tend to reduce spreading tendencies, but concentrations of trajectories or flotsam distributions are unlikely. Over the continental shelf, bathymetric and baroclinic processes can lead to convergences that are typically the same order as the spreading velocities associated with characteristic estimates of ocean turbulence. As these are associated with topographic features and river runoff, they tend to be persistent features and may offer a rationale for developing flotsam search procedures, or at least improving the possibility of more accurate trajectories. Finally, small-scale features associated with tidal movement can produce locally strong convergences that will act as collection mechanisms for flotsam. These cases provide short-term guidance for developing flotsam recovery plans.

In all cases, particularly in open ocean regions, the prospects of recovering low-profile flotsam simply by going out and looking for it, are not good. The odds of recovery periods of a few days may be improved significantly if the flotsam's visibility can be enhanced either optically or electronically. This suggests that valuable or troublesome objects should be fitted with such devices as emergency locator transponders and strobes.

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TOWARD A POPULATION DYNAMICS OF MARINE DEBRIS

Tim Gerrodette

Southwest Fisheries Center Honolulu Laboratory
National Marine Fisheries Service, NOAA
Honolulu, Hawaii 96812

ABSTRACT

Adopting a population dynamics viewpoint can provide a useful overview of the problem of marine debris. This paper outlines the information needed to establish an understanding of the population dynamics of marine debris, notes existing sources of data which could provide such information, points out potential gaps of information, and suggests experiments or sampling which could help fill those gaps. First, a typology of marine debris is needed; because the kinds of marine debris vary so widely, separate estimates of "birth" and "death" rates will be needed for each "species." Data on birth or generation rates of marine debris must include not only "species" and abundance, but location and seasonality. Mortality or degeneration rates of marine debris can be summarized with a survivorship curve. Although decay of the material is the only true death, for certain applications debris can be considered dead by being cast on a beach or by sinking to the ocean bottom. Fouling organisms may contribute to decreasing buoyancy and hence hasten the sinking of objects such as ropes and trawl netting. An important question is the choice of units to be used in a quantitative description of marine debris. The choice of units will depend on the type of debris, and meaningful units should have the property of independence. The choice of units will also reflect whether the impact of marine debris is being measured on fish stocks, fishing operations themselves, vessel navigation and safety, or marine bird and mammal populations.

INTRODUCTION

As the final formal presentation of this workshop, this paper will attempt to provide an overview of the technical aspects of the marine debris problem, especially as identified in the last few days, to note gaps in our information which need to be filled by future research, and to make some provocative comments which may stimulate thinking in the working group sessions which are the next phase of the workshop. As a conceptual framework for the discussion, I propose to talk about debris in terms of population dynamics, that is, to treat debris as a population of objects

whose dynamics we wish to describe. As with a biological population, the main tasks are to determine how many new individuals are entering the population (through births and immigration) and how many individuals are leaving the population (through deaths and emigration), per unit time. From this information, the number of individuals of each kind of debris present at any time can be calculated.

Why should we be interested in the dynamics of marine debris? Certainly there are aesthetic reasons for objecting to the amount of junk in the sea. We should not ignore these reasons, since for the general public these reasons may be most important to mobilizing people to help, as the Oregon experience (Neilson 1985) has shown. There are also a number of more technical reasons to be interested in the amount and dynamics of debris. The papers in this workshop have emphasized the impact of debris on marine mammal, bird, and turtle populations. What deserves more emphasis is that there are strong reasons for fishermen and fishery scientists to be concerned about the amount of debris in the ocean. Debris can interfere with fishing operations by fouling nets or traps. When it fouls a ship's propeller, debris becomes a serious navigational hazard. And when lost gear continues to fish, it is an unreported source of mortality not taken into account in calculations and recommendations for management of the fishery resource.

Our perception of which kind of debris is of greatest interest and importance will depend on whether we are measuring the impact of debris on fish, seals, or ships. A drifting hawser might be a navigational hazard for a ship, but poses no danger to a seabird, while the plastic top of a six-pack of beer is more dangerous to a seabird than a ship. People with different interests may therefore have different perceptions of how serious the problem of marine debris is and what should be done to correct it.

Population Statics

The population dynamics of marine debris is a new scientific discipline. Before we can get to the dynamics, therefore, we must deal with some preliminary population statics. The first problem is to identify the different kinds of debris. Following our biological metaphor, we may call these different "species" of debris. Several papers in this workshop have presented "species lists," especially from the Pacific (Dahlberg 1985; Merrell 1985; Neilson 1985). The wide variety of debris means that the population dynamics may be different for each "species." Furthermore, we should keep in mind that new "species" may evolve in the future.

Estimates of standing stock sizes of marine debris may be given either as absolute or relative abundance. In this workshop, several papers have reported relative estimates of stock size, either from beach surveys (Merrell 1985) or as sightings from a ship (Dahlberg 1985; Jones and Ferrero 1985). Although an estimate of standing stock only describes the population at a particular point in time, a temporal series of snapshots of the population can provide clues to the dynamics of the population. Abundance can increase or decrease, and "species" composition can change. Usually the main problem with determining trends in abundance is the standardization problem: data have been taken at different times of day, under different weather conditions, from different heights above the ocean

surface, from different beaches, and so on. A simple, standardized program of observation and sampling will therefore often give more useful results than a more elaborate, but inconsistent, program.

Jones and Ferrero (1985) have summarized clearly the problems with estimates of debris abundance made from ships. Some types of debris are much harder to see than others, size is very hard to estimate since large parts of some items are submerged, and in any case the sighting probabilities depend on sea state, buoyancy, color, and other factors. These are serious problems which must be overcome if sighting rates of debris are to be translated into estimates of absolute abundance. But shipboard sighting rates of debris can still be useful as relative abundance indicators. Programs of regular searching for marine debris could be expanded to include more vessels wherever such observations do not interfere with the normal mission of the ship. We should think about more passive and automatic means of collecting data. Perhaps high-resolution sonar could be used to detect large pieces of gear, or a simple grappling hook could be towed behind the ship. Collecting data in several different ways has the additional advantage that we can gain some insight into how some observations may be biased. For example, we could compare visual observation of debris from a ship with the amount caught on a hook during the same period. Or we could compare the amounts caught on several hooks towed at different depths.

We have to choose some units to describe the stocks of debris. Merrell (1985) reported the amount of debris on Alaskan beaches both as number per kilometer and as kilogram per kilometer and noted that number and weight did not always show the same trends. For debris items which are discrete and which come in similar sizes, the number of each "species" will be a suitable unit, but for others which come in variable sizes, the choice is not so easy. With fragments of nets, for example, we could use number, weight, linear measure, or surface area. What is the best unit to describe this population? Suitable units should express an equal impact and be independent of one another. If we choose numbers of net fragments as our unit, it implies that a 100-m net fragment has the same impact as a 10-m fragment. If we choose a linear measure, it implies that a 100-m net fragment is equal in its impact to ten 10-m fragments. Which is true for the impact on fish stocks? Which is true for the impact on marine mammals? This is an area for future investigation. Ideally, we would like to use a unit which is more closely related to the impact the debris is causing, such as the relative fishing powers of 10- and 100-m net fragments. This, however, requires a clearer mechanistic understanding of how drifting net fragments affect fish, mammal, and bird populations. For the present time, we will simply note that an appropriate choice of units to describe debris depends on (1) the type of debris, and (2) the target population--that is, whether the impact of debris is being measured on fishing operations, on vessel safety, or on fish, mammal, bird, or turtle populations.

Population Dynamics

Now we come to the dynamics of marine debris. Individual items of debris can enter the population through births or immigration and leave it through deaths or emigration. Let us leave aside the discussion of birth and death rates for just a moment and consider the migration of marine

debris. Since debris cannot swim, we assume that a good approximation of migration routes can be calculated from a knowledge of ocean currents (Reed and Schumacher 1985; Seckel 1985). Individual items which are highly buoyant, such as styrofoam objects, might be influenced by wind more than currents. This makes the problem a bit more complicated, but since general wind patterns are well known and the relative contributions of wind and current can be estimated, this presents no fundamental problem. In general, then, the migration patterns of marine debris can be fairly well estimated for any "species" of interest from existing information on currents and winds. It is well to remember that much of our knowledge of surface currents comes from observation of scientific floating objects--drift bottles and buoys--so that knowledge should be quite applicable to floating debris.

The heart of population dynamics is the estimation of birth and death rates. We would like to be able to describe how many new nets are "born" each year in the ocean. We would like birth rates to be broken down by "species," location, season, and type of fishing operation. Now of course one of the basic differences between biological species and debris "species" is that biological individuals reproduce their own kind, while debris is produced as a result of man's activities. We therefore expect that for marine debris, in contrast to a biological population, there will be no relation between recruitment and standing stock. Instead, birth rates will be related to amount of fishing. Actually it is possible that this may not be strictly true and that there may be some stock-recruitment relationship for marine debris. If objects of debris interfere with fishing operations and cause other gear to be lost, then the stock is contributing to the recruitment of new individuals in the population. For example, a large ball of trawl netting may foul a gill net and cause it to break away or to be abandoned.

Like human births, we can divide births of marine debris into two kinds: planned and unplanned. The marine debris equivalent of planned parenthood is the deliberate dumping of trash or worn-out gear at sea. Unplanned parenthood is the accidental loss of gear. Data on accidental losses could be estimated by reports from fishermen or from observers on fishing boats (Low et al. 1985). If average rates of gear loss for various types of fishing operations could be calculated, they could then be applied to total fishing activity. Such estimates would be minimum estimates of birth rates since births due to deliberate dumping are not included. Certainly, we need more information on these deliberate births.

The estimation of mortality rates presents other problems. First of all we should consider the meaning of death for marine debris. The decay or disintegration of debris is certainly death, but effective death might occur before that. It depends on which group we are measuring the impact of debris. Debris which sinks is removed from the population as far as pelagic fishing operations are concerned, but not as far as benthic fishing operations are concerned. Debris cast ashore is removed from the population as far as vessel safety is concerned, but not as far as seals are concerned. This means that we will have to decide on what group we are measuring the impact of debris before the meaning of death is clear.

The decline in abundance over time in a population can be summarized with a survivorship curve. Figure 1 shows three general shapes that

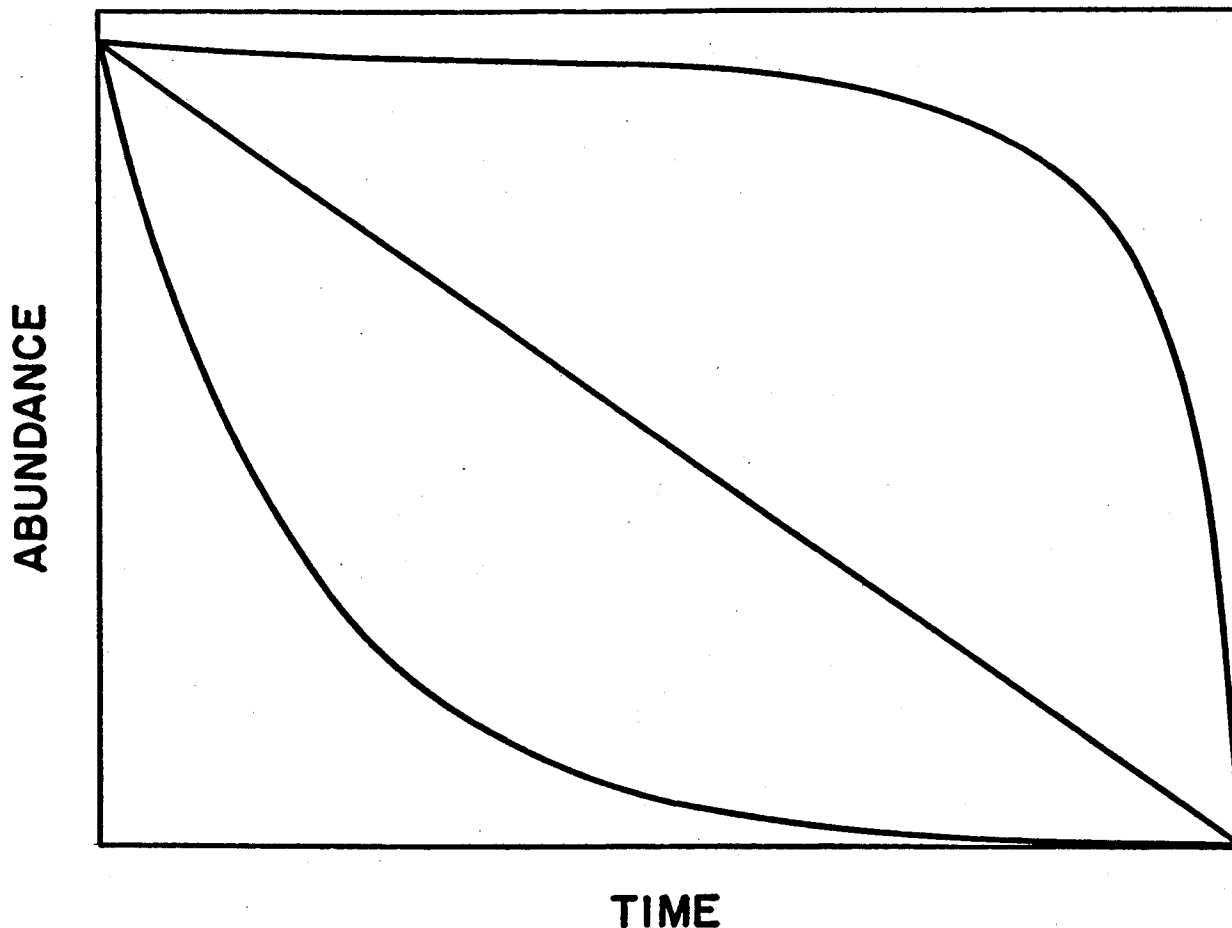


Figure 1.--Three general types of survivorship curves.

survivorship curves of marine debris might take. The top curve shows a population in which most individuals survive for most of the lifespan, then become "senescent" more or less simultaneously. In the middle curve, a constant number of individuals die in each unit of time, while in the lower curve, there is a constant rate of mortality per unit of time. Different "species" of debris will certainly have different survivorship curves. We need to establish the general shape of the survivorship curve for each "species" and to establish the time scale along the horizontal axis. Does it take days, months, or years for debris to die?

Another factor we need to consider is that although an individual item of debris may not die by disappearing from the ocean, it may change its condition in such a way that it becomes less effective. Carr et al. (1985) and High (1985) reported observations particularly directed at this important question. The impact of a lost gill net is quite different depending on whether the gill net is stretched open or tangled up. Even if a drifting net remains open its effectiveness must decline with time as it becomes fouled with algae, barnacles, and other organisms. Figure 2 shows some simple hypothetical possibilities of decline in effectiveness over time. The top curve shows a situation in which effectiveness remains high for a while, then declines rather rapidly. The middle figure shows a

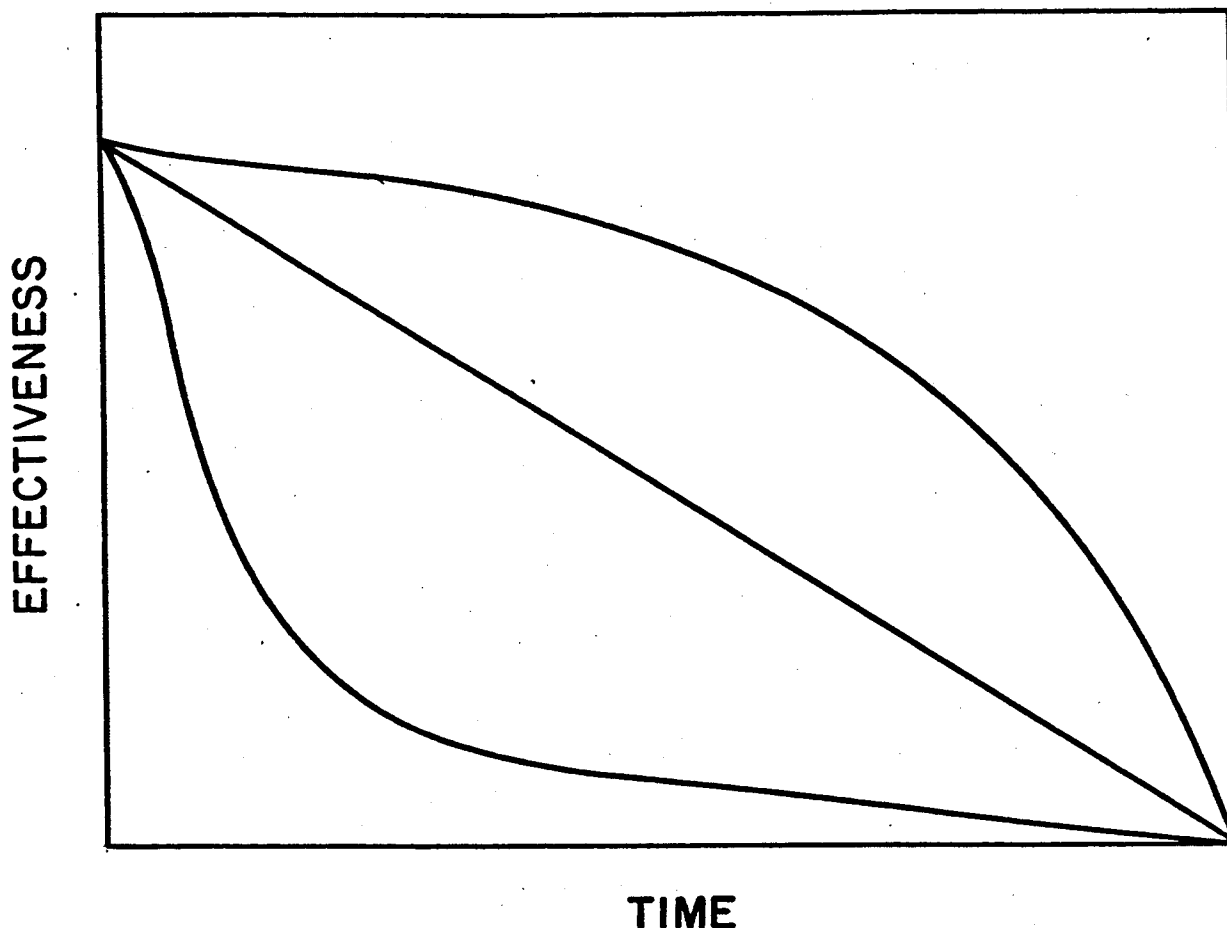


Figure 2.--Several possibilities for declining effectiveness of individual items of marine debris with time.

linear decrease in effectiveness with time, while the lower curve illustrates a situation in which there is an initial rapid decline followed by a longer period in which the debris continues to have an impact, though at a reduced level. As with survivorship, the important things we need to establish are the general shape of the effectiveness curve for each "species" of debris and the time scale on the horizontal axis.

The impact of a population of marine debris is a product of the effectiveness and survivorship curves. Figure 3 illustrates this idea. As a simple example, linear declines in relative effectiveness and in abundance with time are shown. Their product, however, which indicates the impact of this particular "species" of debris, is not linear. Putting it more formally, let $q(t)$ be the average effectiveness (catchability coefficient in fisheries parlance) and $n(t)$ the number of items of a particular debris "species," both functions of time. Then the total impact of (e.g., total number of fish caught by) this kind of debris is

$$\int_0^T q(t) n(t) dt .$$

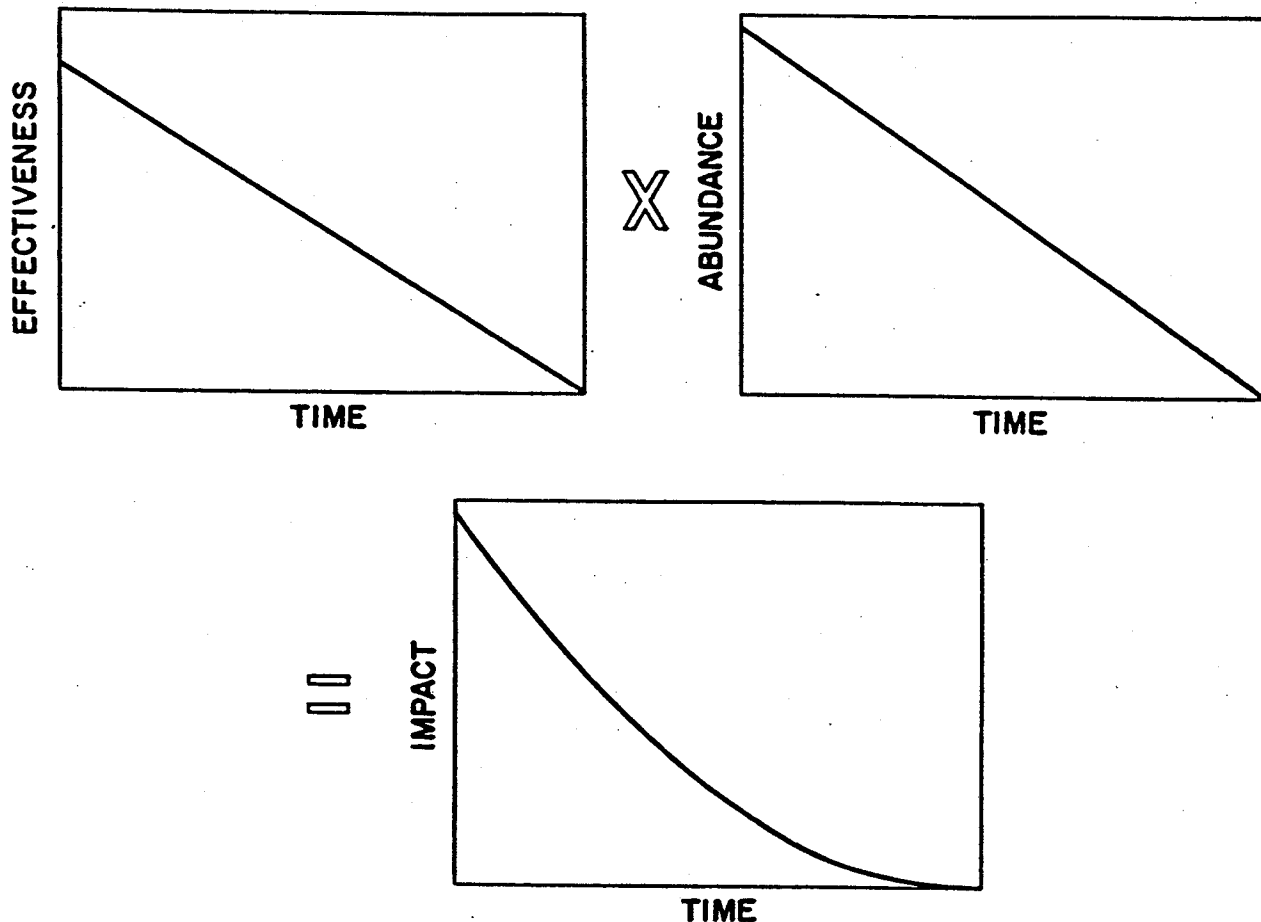


Figure 3.--Impact of a population of debris as a function of time. The impact is a product of the effectiveness and abundance functions.

There are three general causes of death: (1) deterioration of material as a result of exposure to seawater, sunlight, oxidation, biological agents, and the mechanical agitation of the ocean; (2) sinking by loss of buoyancy through water absorption and by fouling with marine organisms; and (3) stranding of material on the shore. What fraction of deaths is due to each of these three causes? At the present time even rough estimates do not seem to exist for floating marine debris.

The physical deterioration of rope and netting material could be estimated from the manufacturer's specifications; otherwise some simple experiments could show how long various materials might last. In general, we know that modern synthetic materials have a long life. In fact, it is the durability of these materials that is one of the fundamental causes of the debris problem. Given this long potential life, what does eventually happen to marine debris? If it does not deteriorate, and if it is not ingested by a marine organism, there are only two other ways it can die: either it sinks or it is cast up on a beach.

Loss of buoyancy can occur when an item of debris gradually absorbs water and also when marine organisms grow on it. The main organisms which could grow on floating debris and weigh it down are certain species of barnacles. Since the calcified barnacle shell is denser than water, a heavy growth of barnacles could cause an object which was originally slightly buoyant to become heavier than water and sink. How quickly this will happen depends on the original buoyancy of the object, and on the rate of settlement and growth of barnacles. Figure 4 illustrates this for three items of debris with different original buoyancies. The items of debris have positive buoyancies which decrease only slightly with time. The negative buoyancy of barnacles changes greatly with time, probably according to some S-shaped curve similar to the one shown. The first item of debris is so buoyant that barnacles will never cause it to sink. The second item of debris requires a heavy growth of barnacles to develop before it will sink, while the third item is only slightly buoyant and is quickly pulled down by the barnacles. The greatest unknowns are the rates of settlement and growth of the barnacles (and other organisms denser than seawater), but these could be established with some relatively straightforward, though not necessarily easy or cheap, experiments.

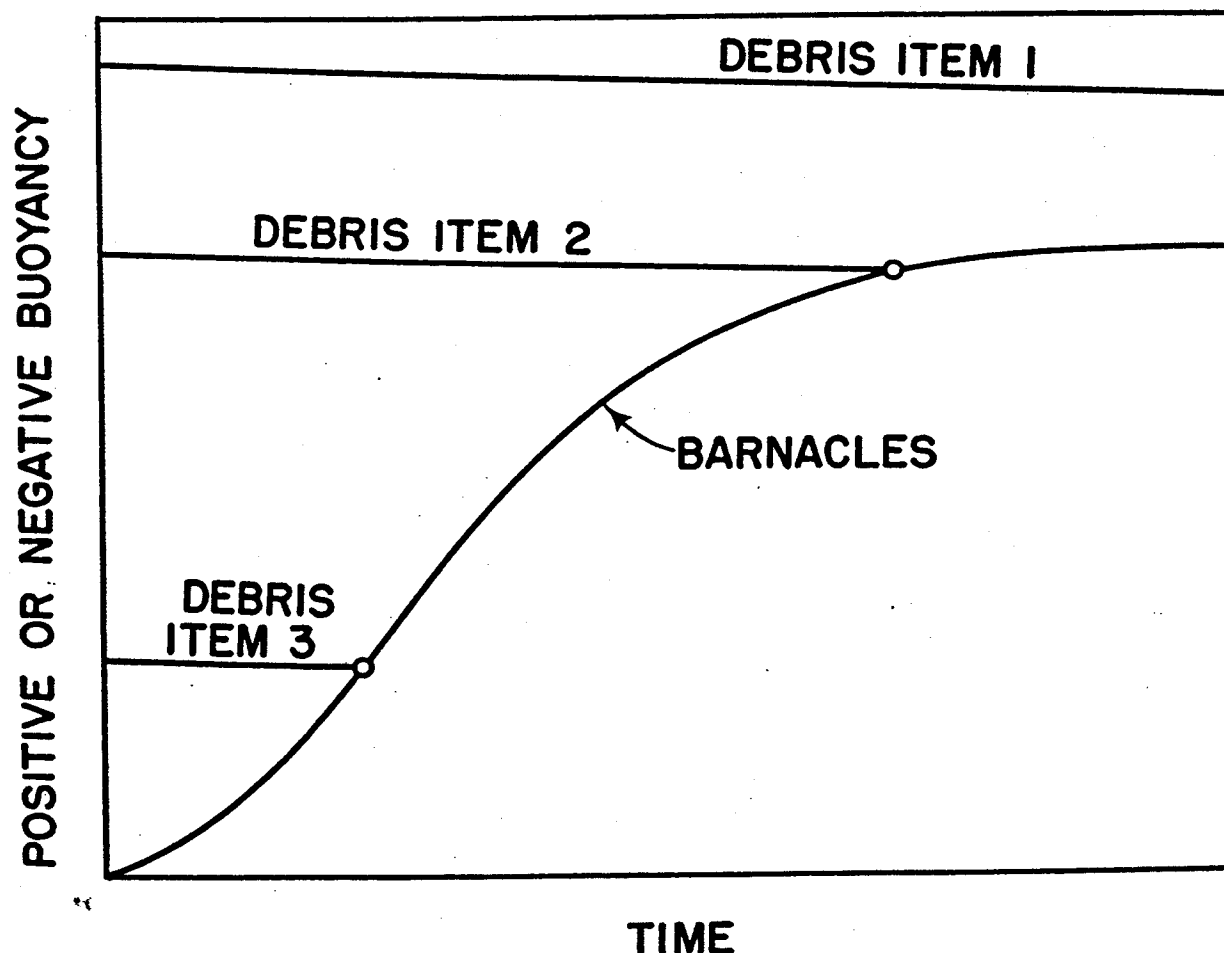


Figure 4.--Possible changes in buoyancy of items of debris with time due to the growth of barnacles or other organisms with density greater than that of seawater. In the examples shown, the growth of barnacles would cause debris items 3 and 2 to sink, but not item 1.

What happens after an object has begun sinking depends on several factors. Of course if the object is dense enough it will continue to sink to the bottom of the ocean. But if its density is close to that of seawater, the compressibility of the material relative to that of seawater is important. Material which is more compressible than seawater will continue to sink, even when the barnacles die and fall off deep in the ocean. On the other hand, material less compressible than seawater could sink to and remain at an intermediate depth.

The third possible fate of an item of marine debris is stranding on a shore. It is difficult to estimate how much material is eventually removed from the ocean in this way. Monitoring a beach and recording the amount of debris which accumulates may give a relative indication of abundance, but it does not tell us what fraction of a particular kind of debris ends up on a beach. Nearshore this fraction could be substantial. One possible approach in coastal waters is to attach sonic or radio tags to a sample of debris and monitor the fate of these tags. Such an experiment would also have to consider the possibility that some items of debris could be deposited on a beach, but later washed out again; these could be termed "born-again" debris. Away from the continental land masses, on the other hand, the probability of death due to deposit on a beach appears to be quite low. Since the oceans move in large circular gyres, and since surface waters tend to converge toward the centers of these gyres, a floating object, if it did not deteriorate or sink, could continue to go around and around. There is anecdotal evidence for some objects being afloat for many years.

SUMMARY AND CONCLUSIONS

This paper has provided a brief description of the marine debris problem, approached from a population dynamics viewpoint. This description addresses mainly the fate of marine debris. It concentrates on describing how much, when, and where. From this information, the impact of a given amount of debris on fishing operations or on vessel safety could be estimated by computing an encounter rate. To estimate the impact of this debris on populations of fish, birds, turtles, and mammals, however, would require more than a simple encounter rate. It would also require information on the behavior, physiology, and ecology of these animals, topics beyond the scope of marine debris population dynamics.

Attempts to reduce the amount of marine debris can be viewed as taking one of two basic approaches: to increase the death rates or to reduce the birth rates. Programs which remove debris from beaches or proposals to require certain rates of degradability in fishing gear are aimed at increasing death rates of debris. Programs which seek to reduce the amount of debris created, either through legal or financial incentives, are aimed at reducing birth rates. Either can be an effective means of population control. I hope we can find a suitable combination of these two approaches in the working group meetings which are next.

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THE OCEANIC CIRCULATION IN HAWAIIAN WATERS: FACTS,
HYPOTHESES, AND PLANS FOR FURTHER INVESTIGATIONS
(Abstract only)

Lorenz Magaard
Department of Oceanography
University of Hawaii
Honolulu, Hawaii 96822

ABSTRACT

According to Robinson (Eddies in Marine Science, New York, 1983), "It is now well known that the mid-ocean flow is almost everywhere dominated by so-called synoptic or meso-scale eddies." This is even more true near major topographical features like the Hawaiian Ridge where, in addition to quasi-geostrophic motions (Rossby waves, synoptic eddies), barotropic and baroclinic tidal currents and currents associated with wind waves and surf, are of strong, and in some locations of dominating influence.

Examples of direct and indirect current observations will be presented. These observations illustrate how extremely difficult the predictions of the fate of marine debris in the Hawaiian waters is.

In view of the very limited knowledge that we have about the oceanic circulations in Hawaiian waters, a major research project, called "Hawaiian Ocean Experiment (HOE)," is planned for the period 1986-91. Background and plans of this comprehensive, interdisciplinary, cooperative oceanographic study of Hawaiian waters (to include the inhabited Hawaiian Islands and the Northwestern Hawaiian Islands) will be outlined.